TECHNICAL COST MODELING

OF PLASTICS FABRICATION PROCESSES

by

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ABSTRACT

A methodology is developed for creating computerized models that estimate the cost of producing components by plastics fabrication technologies.

The technical cost modeling methodology involves dividing the total cost of a process into the individual elements that contribute to that total. Based on theoretical considerations, engineering judgments, and statistically derived relationships, equations are developed to estimate the individual elements. The technical cost model is the synthesis of these equations into a computerized framework.

The structure, details, and assumptions of technical cost models for three fabrication processes are presented; namely, injection molding, SMC compression molding, and filament winding. For each model, a case study of the use of the model is also presented. Case studies serve to validate the approach and assumptions of the technical cost models, and are an integral part of the technical cost modeling methodology.

Cost models can be used to estimate the cost of fabricating a wide range of different components. They can also be used for performing sensitivity and comparative cost analyses. Examples of sensitivity analyses are presented for the injection molding case study.

The complexity of cost models is effected by the number of operations involved in the process, and by the relationship of the operations to each other. The SMC and filament winding models both involve two operations, each coupled in a different fashion; the SMC model uses cost coupling, the filament winding model uses rate coupling.

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LIST OF ILLUSTRATIONS

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INTRODUCTION TO TECHNICAL COST MODELING

Using a new technology to produce manufactured goods engenders a wide range of uncertain engineering and economic consequences. While considerable talent can be brought to bear on the engineering issues, many economic questions usually remain. This problem is particularly acute when the new technology is not fully developed, since cost analysis is typically based upon experience, historical data, and somewhat ad hoc accounting practices.

Historically, new technologies have been introduced incrementally, and the economic consequences measured directly. While this trial and error testing has never been optimal, in the past it may have been good enough. As the number of available alternatives continues to grow, the disadvantages of relying on a trial and error methodology also grow.

An alternative testing methodology, technical cost modeling, can be used to analyze the economic consequences of alternative manufacturing processes without the prohibitive economic burden of trial and error innovation and process optimization.

Technical cost modeling is an extension of engineering process modeling, with particular emphasis on capturing the cost implications of process variables and economic parameters. By grounding the cost estimates in engineering knowledge, critical assumptions, such as processing rates and energy and materials consumption, interact in a consistent, logical, and accurate framework for economic analysis.

Because of their parameterized structure, technical cost models can be readily tailored to a wide range of operating conditions, simplifying the

economic analysis of technological changes. Furthermore, these models are flexible, allowing users to tailor them to their own cost estimating environment. Once modified, these models can be used to explore in detail the costs of competing processes and materials for a particular application.

Using technical cost models, a decision such as whether to blow mold or injection mold an access door panel can be investigated without extensive expenditures of capital and time. Technical cost models can establish direct comparisons between processes, they can access the ultimate performance of a particular process, and they can be used to identify limiting process steps and/or parameters.

This thesis examines and illustrates the techniques of engineering cost analysis through a description and application of three models: injection molding, SMC molding, and filament winding. The thesis begins with a description of the most commonly used alternative approaches to cost analysis, summarizing the advantages and weaknesses of each.

Next, the generic elements of manufactured part cost are presented, defining fixed and variable elements, and listing typical examples of each. Additionally, general techniques for estimating these elements are discussed. Finally, methods for estimating other manufacturing parameters including process rates, rate balancing, and process coupling are discussed.

Three technical cost models - injection molding, SMC, and filament winding - are separately described in the upcoming sections. These three models were selected from ten that were developed over the course of this

research project. Each successive model incorporates an added degree of complexity, and these differences are described.

The models and methods described herein are based on industry data, and they have been tested in numerous industrial instances. Therefore, the conclusions of this thesis fall into two categories. First, there are general conclusions about the technical cost method. Second, there are specific conclusions regarding the economics of the fabrication processes that are described.

COST ANALYSIS METHODS

A variety of techniques are currently used to estimate the cost of a manufactured plastic component, each the product of a particular cost accounting philosophy, and limited to those situations for which the philosophy applies. Four of the most commonly used cost estimating techniques are described in the following sections. Each description outlines the method, underlying assumptions, and some of the limitations and implications of the technique.

MATERIAL TIMES TWO

To a first approximation, the cost of a manufactured plastic component is frequently estimated as a constant multiple of the cost of the material required to manufacture it. The multiple most commonly used is two - twice the material cost.

The cost estimate generated by this technique is often close to the actual cost of manufacturing a component. This technique has the distinct advantage of simplicity over all other techniques. The reader might be surprised by the number of good business decisions that have been based upon this simple estimating method.

However, this technique has clear limitations. For one, estimated costs are independent of the fabrication technology. Thus, for a given part, the cost of blow molding, injection molding, and thermoforming are identical as long as material costs are the same.

The "material times two" technique also fails to consider the consequences of two major production parameters; cycle time and annual production volume. Yet, these parameters have clear influences on cost: cycle time influences labor content and annual production volume influences the utilization of equipment and the recovery of capital investments.

Finally, like many engineering rules-of-thumb, it does not work well when dealing with extremes. The "times-two" rule is more applicable to commodity materials, since the basis would appear to be the experience gained from years of processing these materials. When processing expensive materials, the results of a "times-two" cost estimate are likely to be inaccurate.

MATERIAL COST PLUS SHOP TIME

The most commonly employed cost estimating technique in the plastics industry is to add the cost of the material to a measure of the cost of the time required to process it. This technique is summarized in the following equation.

$$\text{Cost} = \text{Material Cost} + \text{Machine Rent} * \text{Cycle Time}$$

Unlike the preceding technique, this cost estimating method does capture some of the influence of cycle time on manufactured part cost. Additionally, it separates processing costs from material costs through the

introduction of the concept of a machine rent. Given good values for machine rent and cycle time, very accurate estimates can be attained.

The advantages of this technique are offset by a number of limitations. First, the machine rent figure must be estimated, usually from historical operating expenses. The use of this rent implicitly assumes that the machine will continue to operate as it did in the past.

Second, this technique does not take into account the influences of annual production volume. The method assumes that machine usage is infinitely flexible, and that cost is not influenced by the level of equipment utilization.

Finally, this technique mis-specifies the true influence of cycle time on production cost, by assuming that costs are linear with respect to changes in cycle time. This assumption is not generally true over the range of possible cycle times.

MATERIAL COST PLUS LOADED SHOP TIME

A refinement upon the previous technique is to separate the cost of shop time into a labor element and a direct burden on the labor rate, as illustrated by the following equation.

$$\text{Cost} = \text{Material} + \text{Cycle Time} * \text{Wage} * (1 + \text{Burden})$$

This technique introduces the concept of labor burden, and begins to separate the individual elements of part cost. Specifically, the contributions of direct labor and materials are now directly estimated. This segmentation is valuable for two reasons. First, it enables assessment of the relative contributions of each element to the total cost. Second, it begins to enforce a disciplined approach to cost estimating by focusing attention on the relationship between individual cost elements and the manufacturing process.

Nevertheless, this technique is limited by the quality of the burden and cycle time estimates. While cycle time is directly measurable (although perhaps after the fact), burden can only be accurately measured after completing a production run.

QUOTES

An entirely different approach to cost estimation is to obtain production quotes from manufacturers each time a cost estimate is required. In this method, a detailed engineering drawing or part model is submitted to a molder, and the molder returns a contract price for which he is willing to supply the finished component.

The obvious advantage of this approach is that there is little uncertainty regarding the cost of acquiring the finished components. However, this method does not yield the cost of the component; rather, it yields its price. While it is reasonable to assume that the quoted price is greater

than the manufacturing cost, nothing else can be extracted from this information. In fact, in some instances, the quoted price may actually be lower than the manufacturing costs.

SUMMARY

In addition to the four cost estimating methods described above, numerous other methods may be employed. The proliferation of these techniques both reflects the importance of estimating manufactured part cost and demonstrates that no one technique is universally appropriate or applicable.

While it is possible to point out deficiencies in each technique, it is important to remember that they are used widely, and yield good results when used by knowledgable practitioners. The success of a plastics molding business is critically dependent upon the skill of its cost estimators. Businesses with poor cost estimation practices do not remain businesses for long.

Nevertheless, there are good reasons to use techniques other than those described above. For one, the above techniques generally rely upon the expertise of individuals, whose insights into cost estimation cannot be easily examined. This introduces difficulties when it becomes necessary to transfer expertise to others in the organization. Also, these techniques do not indicate how various factors contribute to manufacturing costs, information that is critical for cost control.

Technical cost modeling is an alternative approach to cost estimation. Through systematic application of engineering and economic principles, it is possible to reduce cost estimation to a system of elemental equations, relating processing parameters, cost elements, and total cost. This approach is described in the following section.

ISSUES FOR TECHNICAL COST ANALYSIS

The technical cost modeling method uses an approach in which each of the elements that contributes to total cost is estimated individually. These individual estimates are derived from basic engineering principles, from the physics of the manufacturing process, and from clearly defined and verifiable economic assumptions. The technical cost approach reduces the complex problem of cost analysis to a series of simpler estimating problems, and brings engineering expertise, rather than intuition, to bear on solving these problems.

In dividing cost into its contributing elements, a distinction is made between costs elements that depend upon the number of components manufactured annually, and those that do not. For example, in most instances, raw materials contribute the same cost regardless of the number of components produced. On the other hand, the per piece cost of tooling will vary with changes in production volume. These two types of cost elements are called variable and fixed costs, respectively, and they form a natural division of the elements of manufactured part cost.

VARIABLE COST ELEMENTS

Variable cost elements are those elements of piece cost whose values are independent of the number of pieces produced. For most plastics fabrication processes the important variable cost elements are:

1. Material,
2. Direct Labor, and
3. Energy.

Each of these cost elements is discussed in detail in the following sections. Issues that should be considered, and general methods for estimating each element, are provided.

MATERIAL

The cost of the material used to construct a component may be directly estimated from the design weight of the part and from the price of the material. However, in some situations, the design weight is not a complete measure of the amount of material that is consumed. Scrap losses must be considered, and they can arise from a number of technical reasons, including start-up losses, spillage, color changes, and sensitivity or inability to reprocess material trimmed from the final part.

In addition, there may be uncertainty regarding the price of the material. Manufacturers list prices are easily obtained; however, they do not always reflect market transaction prices, and both list and transaction prices change regularly. At first glance, material prices would appear to be easy to establish, but in practice, they are also estimated values.

DIRECT LABOR

The cost of direct labor is a function of the wages paid, the amount of time required to produce a piece, the number of laborers directly associated with the process, and the productivity of this labor. However, a number of complexities cloud what appears to be a straightforward estimation.

Labor wages should include the cost of the direct benefits to the laborer, including health and retirement benefits. However, these wages should not include the cost of supervisory or other overhead labor, as these are not usually variable cost elements and should be accounted separately.

The number of laborers directly associated with the process often is a fractional number, and might include portions of machine operators, material handlers, and parts unloaders. Also, labor productivity, which is the ratio of the productive time to the total available time, is difficult to quantify precisely. Finally, even with the body of available engineering information, it remains difficult to estimate accurately the cycle time of most processes.

ENERGY

Ideally, the cost of the consumed energy is estimated by performing an energy balance and by knowing the price of energy. While this sounds simple, performing a detailed energy balance is highly complex. To be accu-

rate, the energy balance must include heat losses, mechanical efficiencies, considerations of heat, mass, and momentum transfer, and potentially, chemical reaction kinetics. Fortunately, for most plastics fabrication processes, this level of detail is not required.

In place of a detailed energy balance, it is often possible to estimate energy consumption by relating it to other production variables. For instance, estimates of the average kilowatt hours per pound of processed material, or estimates of energy consumption as a function of the size of the equipment, can be derived. This approach is acceptable when the cost of energy is small compared to the total cost, or when the estimating relationships are derived from accurate historical data for similar fabricated components.

FIXED COSTS

Fixed costs are those elements of piece cost which are a function of the annual production volume. Fixed costs are called fixed because they are typically one-time capital investments (e.g., building, machinery, or tools) or annual expenses unaffected by the number of components manufactured (building rents, engineering support, or administrative salaries). Typically, these costs are distributed over the total number of components manufactured in a given time period. For most plastic molding processes, the main elements of fixed cost include:

1. Main Machine Cost
2. Auxiliary Equipment Cost
3. Tooling Cost
4. Building Cost
5. Overhead Labor Cost
6. Maintenance Cost
7. Cost of Capital

There are two basic problems to be resolved in all fixed cost estimates: first, establishing the size of the capital investment or annual expense, and second, determining the most reasonable basis for distributing this investment or expense over the products manufactured.

Generally, the first of these issues is the easier to resolve. Either investments are known, or they can be readily established by contacting vendors, reviewing trade journals, or examining historical cost accounts. Alternatively, it may be possible to employ engineering analyses or standard plant practices to estimate equipment costs.

Resolving the second issue involves selecting an appropriate accounting method, some of which are described below.

There is a third important issue which also enters into fixed cost calculations, namely the time value of money. Since most fixed costs are paid off over long periods, the time value of the invested capital must be considered. The time value of money, or cost of capital, is best illustrated by considering interest payments on loans. The lender expects to be repaid more than the amount borrowed, for the privilege of using his capital.

MAIN MACHINE COST

The total cost of the main machine is usually a direct function of its size. Equipment size, in turn, can be related to a number of part parameters. For instance, the clamping force, a measure of press size, can be related to the projected area of the part in many instances. Similarly, equipment might be sized by part weight, length, girth, or volume, depending on the nature of the process.

An issue that can cloud the estimation of machine size is the trade-off that often exists between large, expensive, highly productive machines, and small, cheaper, but less productive machines. This situation is exemplified by the use of multi-cavity tools to produce many parts, simultaneously. These tools are run on large, expensive machines, but significantly reduce the effective cycle time for producing one part. The cost implications of this type of processing are explored in later sections of this thesis.

Once the size of the machine has been established, the investment cost can be estimated by several methods. One method is to use statistical analysis to correlate equipment cost data obtained from vendors to the sizing parameter. Another method is to call the vendor directly for a quote. Engineering estimations of equipment prices can often be obtained from handbooks.

Alternatively, machine costs may be prescribed by the existing physical plant, and can only be based upon recorded values for existing equip-

ment. This would be the case for a molder who is estimating his own production costs.

In conjunction with estimating the capital investment in machinery, a procedure must be established for distributing this investment onto the parts produced. This distribution must take into account the total number of parts being produced, the time over which the parts are produced, and the productive lifetime of the machine.

The simplest method to distribute cost is outlined in the following equation.

Cost Per Piece = Annualized Investment / Annual Production Volume

In this equation, the annual investment cost is divided evenly onto the parts produced in that year. Annual investment is roughly equal to the total investment divided by the number of years the machine is in service. Annual production is the number of a given type of part produced in a year.

The above equation is most applicable to situations which call for dedicated equipment. In these situations, the annual production requirements lead to nearly full or full machine utilization. However, this is not always the case, and the dedicated equipment method is not always appropriate. For situations involving partial machine utilization, or when many different parts are produced with the same machine, the following equation may be more appropriate.

Cost Per Piece = Investment/Volume * (Production Hours/Total Hours)

In this equation, the total annualized investment is again divided by the annual production volume, but in this case, it is also multiplied by a fraction, the ratio of the time required to complete the production run to the total available time. If only half a year is required for the production run, only half of the annual investment cost will be distributed onto those components. This method is equivalent to charging rent for the use of the machine.

The validity of the two capital distribution formulae is case specific; neither one is universally applicable. The choice between these two equations must be made carefully, as the consequences of choosing the wrong one can be quite significant.

In practice, many businesses operate somewhere between the two extremes represented by these equations. Such businesses cannot dedicate a machine to the production of one part, but neither can they keep their machinery fully utilized. For these situations, the two equations provide a means of bracketing the machine cost on a per piece basis.

A final complexity in estimating machine cost arises when two or more processes are coupled together to produce a single part. This is the situation for SMC, where a sheet line makes raw SMC sheet, and a press line molds it into components. It is also true for filament winding, where a part is wound, and then often is cured in an oven or autoclave. For coupled processes, machine sizing may require balancing of the individual

processes. Discussions of the issues of process balancing are provided in later sections of this thesis.

AUXILIARY EQUIPMENT COST

Typical auxiliary equipment for plastics fabrication processes includes dryers, chillers, grinders, bulk storage equipment, and conveyors. Auxiliary equipment costs can be estimated using the same procedures described for main machine costs. Again, from information about the component, including its size, the material from which it is made, etc., it is possible to identify auxiliary equipment requirements. Capital investments for this equipment are estimated from vendor literature, regression analysis, and/or handbooks. Using one of the two capital distribution equations above, the contribution of auxiliary equipment to the cost of the component can be estimated.

The procedure for estimating auxiliary equipment costs can be simplified in many instances by assuming that the ratio of the cost of auxiliary equipment to the cost of the main machine is constant. The validity of this approximation depends on the type of fabrication process being considered. For many plastics fabrication processes, this assumption is sufficiently valid to yield good cost estimates.

One modification to the above assumption is to account for the changes in auxiliary equipment that arise from changes in the material being proc-

essed. This can be done through the construct of a "material adjustment factor", a concept which is discussed more fully in following sections.

TOOLING COST

The cost contribution of the tooling is probably the most difficult element to estimate for two reasons. First, it is difficult to accurately estimate the investment cost of a set of tools. Second, it is difficult to estimate the number of pieces that will be produced on a tool during its productive life.

The capital investment for tooling is a complex function of many variables, including the material of construction, the design and size of the part, the level of process automation, and the quality of the tool. Because tools are often purchased items, additional variables are introduced by differences in manufacturing processes and pricing policies of toolmakers (1).

It is not uncommon for the quotes from two toolmakers for tooling to produce exactly the same part to differ by more than a factor of two, especially if these toolmakers are from different regions (2). Because of these complexities, there are no consistently reliable methods for estimating the capital investment in tooling.

Perhaps the best method for estimating tooling investments involves the use of regression analysis. Historical investment data are collected and analyzed to evaluate correlations between the investment and various

explanatory production variables. Typical explanatory variables include part size, weight, and material, annual production volume, and even the name of the toolmaker. Once a significant correlation is established, this relationship can be used to estimate the investment cost of tooling for similar components.

Using regression analysis to estimate tooling investments has a number of pitfalls, including implicitly assuming the future will be similar to the past. Nevertheless, when applied judiciously, it is a powerful cost estimation procedure.

Problems associated with estimating tool-life are almost as complex as those of estimating the investment. Tool life is a function of the design of the tool, the material of construction, the annual production volume, and the maintenance procedures. Fortunately, for many plastic components and fabrication processes, the tools outlive their usefulness (i.e., the product becomes discontinued before the tool wears out). When this is the case, the contribution of tooling to the total piece cost can be estimated by distributing the capital investment over the annual production volume for the life of the production run.

BUILDING COST

The investment cost of the required building space is relatively straightforward to estimate given the amount of space required and the price per square foot of factory floor space. The first of these parame-

ters can be obtained from equipment vendors, or it can be estimated by viewing similar facilities. Values for the second parameter can usually be obtained from real estate salepersons or from published literature. Alternatively, the building may already be purchased or leased, and the costs well known.

Distributing the building investment onto the parts produced can be done using whichever of the capital distribution equations described earlier is more appropriate to the situation being considered.

OVERHEAD LABOR COST

Overhead labor costs are the salaries of supervisors, janitors, engineers, accountants, and other personnel not directly associated with the production process, but required nevertheless. The contribution of overhead labor to piece cost is virtually impossible to estimate explicitly, unless the operation in question involves the production of only one component.

Instead, the most common practice of accounting overhead costs is to establish variable or fixed burden rates. Burden is a construct that assumes a constant ratio between overhead labor costs and another element of piece cost. Variable burden usually assumes that overhead labor is proportional to direct labor; fixed burden assumes it relates to other fixed costs.

Burden rates are usually estimated by accountants reviewing historical financial data. In lieu of historical information, estimates of typical

burden rates for various operations can be obtained from sources, including trade organizations (e.g., Society of the Plastics Industry) (3) and government publications.

The use of burden to account for overhead labor costs greatly simplifies the estimation procedure. However, there is a danger to using this approach. If burden is a constant number, those components, machines, or processes that require more than the average amount of overhead support are effectively subsidized by those requiring less support. This can lead to underestimating the cost of the more difficult operations and overestimating the cost of the easy ones. It is therefore recommended that burden rates be frequently reviewed and adjusted according to the specifics of the operation.

MAINTENANCE COST

The cost of maintaining capital investments, including tooling, the main machine, and auxiliary equipment, are also difficult to quantify precisely. Maintenance is often unscheduled, done in response to problems as they develop. To accurately estimate the cost of maintenance requires accurately predicting probabalistic events.

One common approach to estimating maintenance costs assumes that they are equal to a fraction of another cost element, usually the cost of the investment that is being maintained. This approach simplifies the computa-

tion, but suffers from the same drawbacks that characterize the use of overhead burdens.

COST OF CAPITAL

The cost of capital is a fixed cost element that accounts for the time value of money. It is equivalent to the interest portion of a loan payment, and is considered to be a fixed cost because, over the course of an accounting period, its total value is independent of the production volume. On a piece cost basis, the cost of capital varies inversely with production volume.

Equations for estimating loan payments can be found in most textbooks on engineering economics. While there are a number of variations to these equations, the simplest and most widely used is the simple-interest capital recovery equation, presented below.

$$\text{Payment} = \text{Investment} * (i\ (1+i)^n) \ / \ ((1+i)^n - 1\ )$$

In this equation, "i" is the interest rate and "n" is the number of periods over which the investment is recovered. The term within the parenthesis is called the capital recovery factor.

The above equation calculates total payments, including both the interest and principal portions of capital recovery. However, the "cost of capital" element is just the interest portion of this total. To isolate

the interest portion, the principal is subtracted from the total. In the models described in the following sections, it is assumed that the principal portion is constant in all payment periods. The quotient of the investment divided by the number of payment periods is subtracted from the payment value calculated above. The equation for computing the cost of capital becomes:

$$\text{Cost of Capital} = \text{Investment} * ((i\ (1+i)^n) / ((1+i)^n - 1) - 1/n)$$

This equation computes the average "cost of capital" over all capital recovery periods. Computing the cost of capital in this manner eliminates the need for knowing the age of an investment by treating the interest portion as if it is constant throughout all recovery periods. For most loans, this is not true. Rather, the initial payments consist of mostly interest, while the final payments are mostly principal.

The alternative to the approach outlined above is to establish the age of each capital investment, and use this information to accurately compute the interest and principal fractions of capital recovery. For purposes of general cost estimation, this is rarely worthwhile. Only when tax considerations are important is it worth the added effort. (Taxes are affected by the interest and principal portions of capital recovery in different ways. Discussion of these differences is beyond the scope of this thesis.)

A cost of capital is incurred for each investment that ties up money, including investments in material inventories and payrolls. For short term

investments like these, the construct of working capital has been developed. Working capital is the amount of money required on-hand to conduct the day-to-day aspects of a business. Working capital can be treated as any other investment, and charged for the time value of money. Often, working capital is estimated as being equal to one, two, or three months of variable costs (materials and labor).

SUMMARY OF FIXED AND VARIABLE COSTS

On a cost per piece basis, variable elements do not depend upon the number of components manufactured annually. Regardless of whether one or one million parts are produced, the contribution of a variable element to piece cost is the same.

On the same basis, the fixed elements do depend on the annual production volume. The investment in a fixed cost element (e.g. a machine or building) is constant over a given time period. This investment is divided by the number of parts produced during a period, and if more parts are produced, the cost per part becomes smaller.

While these definitions work well in theory, in practice many cost elements lie somewhere between being variable and being fixed. For instance, material cost per piece (a variable element) may decline if a sufficient number of pieces are produced to justify a discount in the purchase price of the raw material. Similarly, the total annual maintenance

costs (fixed), particularly for maintaining tooling, can be expected to increase with greater production volume.

Distinguishing between variable and fixed costs does not imply that a difference exists in any absolute sense. Rather, the distinction is made to simplify the computational burden of estimating each item. As such, it is a structural assumption of the cost estimation methodology, and should be carefully reviewed for appropriateness.

To estimate fixed and variable costs, several parameters that are not cost elements are required. Estimating values for these parameters is an equally important aspect of technical cost estimation. Issues in estimating two of these process parameters are discussed in the next section.

PROCESS PARAMETERS

Two process parameters that are usually integral to a manufactured part cost analysis are the cycle time and number of parallel production streams. These parameters are discussed below.

The definition of cycle time depends upon the process being considered. The cycle time of plastics molding processes, including injection, compression, reaction-injection, and blow molding, is usually measured in seconds from mold close to mold close. The cycle time for filament winding is typically the time interval between the start of wrapping successive mandrels. For continuous processes, including extrusion and

pultrusion, there is no cycle time. Rather, processing rates are measured in feet per minute, or pounds per hour.

A number of factors can influence the cycle time of a given process, including heat transfer rates, chemical reaction rates, mold filling rates, and the speed at which the equipment "dry-cycles" (i.e., runs when not molding a part). How much these factors effect the cycle time depends not only on the process, but also on the product being manufactured and the material being processed.

If the cycle time is determined solely by factors like those listed above, it is considered to be the "natural" rate of the process, i.e., the rate at which the process runs given no external influences. The "natural" rate of a process represents an upper limit to its rate of operation. In practice, many plastics fabrication processes, including most injection molding and SMC operations, operate at or near to their "natural" rates.

In many situations, particularly when two or more processes are coupled together in a production stream, requirements for line balancing will establish the cycle time. In these situations, one of the processes may be rate limiting, and will establish the cycle time of the other. For instance, when filament winding is directly coupled with slower curing processes, the effective winding cycle time may be longer than the "natural" winding rate.

Cycle time, whether set "naturally" or by other considerations, effects most of the elements of manufactured part cost. The effect of cycle time on the variable cost elements is relatively straightforward. It

does not usually effect material costs or energy costs, significantly. It directly influences the labor cost, by setting the labor content.

The effect of cycle time on the fixed cost elements is more complex. Cycle time effects fixed costs by establishing, for a production run, the total amount of time required to complete the run and the number of parallel processing streams that are required. Multiple or parallel processing streams are required when one machine cannot complete the production run by the prescribed deadline.

The number of parallel processing streams can be estimated from the ratio of the cumulative cycle time for the production run to the amount of time available during the run. This ratio, rounded up to the next integer value, is the number of machines, tool sets, etc. that are required. As cycle time increases beyond threshold values, additional processing streams are required. In the extreme, when the cycle time becomes as long as the allotted production time, one machine is required for each part to be produced.

The effect of the number of streams upon piece costs depends on whether or not the equipment is dedicated to the production of one component. If the equipment is dedicated, the contribution of fixed costs can be computed by dividing the annual investment by the annual production volume. In this case, fixed costs will not change with cycle time, except when the number of process streams changes. Until the number of process streams changes, the same investment is being distributed onto the same number of parts, independent of the time required.

With dedicated equipment, once the number of process streams changes, both the total capital investment and the fixed costs per piece change. However, this only occurs with a change in the number of streams. In all other instances involving dedicated equipment, fixed costs are not sensitive to changes in cycle time.

On the other hand, for non-dedicated equipment, fixed cost elements vary directly with the cycle time. As cycle time increases, so does the amount of time required to complete a production run. As the production hours increase, the fraction of the investment that is distributed onto each part increases.

Fixed costs are directly effected by cycle time when the equipment is non-dedicated. The cost of non-dedicated equipment can be viewed as rent, and the longer you rent, the more you pay.

For similar reasons, non-dedicated equipment costs are uneffected by changes in the number of parallel processing streams. When an additional process stream is added, the incremental cost of doing so is the rent of that machine multiplied by the amount of time that it is required. In contrast, for dedicated equipment, the incremental cost of an added stream is the total investment in that stream.

Tooling is one element of fixed costs that must always be considered dedicated. Tools are dedicated to the production of a single component by default. Therefore, cycle time never effects the per piece cost of tooling, except when a change in the number of processing streams is involved.

In summary, the per piece cost of dedicated equipment is not effected by changes in the cycle time, except when a change in the number of process streams results. For non-dedicated equipment, piece costs vary directly with changes in cycle time, but are independent of incremental changes in the number of processing streams.

SUMMARY OF TECHNICAL COST ANALYSIS

The preceding sections introduced the concepts of variable and fixed cost elements, and provided examples of each. Many of the issues that must be considered in estimating their values were identified. Finally, the effects of cycle time and the number of parallel processing streams were discussed.

This reckoning of the cost is in no way complete. One reason is that very few components are manufactured by a single primary operation. Secondary operations, such as painting, decorating, plating, quality control, packaging, and shipping, are generally required, and these operations can add significantly to the total cost. While the cost of each secondary operation can be separated into variable and fixed elements, these elements may be different from the ones identified for the primary processes.

The preceding sections have outlined the underlying principles of technical cost analysis, and should not be considered to represent a road map. The key principles of technical cost analysis are:

1. Primary and secondary processes contribute to the cost of a finished component,
2. The total cost of a process is made up of many contributing elements that can be classified as either fixed or variable, depending upon whether or not they are effected by changes in the production volume,
3. Each element can be analyzed to establish the factors and the nature of the relationships that effect its value,
4. Total cost can be estimated from the sum of the elements of cost for each contributing process.

One advantage of this approach over simpler cost estimating techniques is that it not only provides estimates of the total cost, but also provides a breakdown of the cost of each contributing element. This information can be used to direct efforts at cost reduction, or it can be used to perform sensitivity analyses, answering questions like, "What if one of the factors should change?".

One disadvantage of this approach is that it is time consuming to generate cost estimates in this manner, and the complexity of generating these estimates can lead to mistakes. The solution to both of these problems is the computer. While developing a computer program for performing elemental cost analyses is still time consuming and complicated, once it is developed, it can be used to generate estimates both rapidly and without fear of mistakes.

The author has developed computer programs for estimating the costs of the following fabrication processes:

1. Injection Molding
2. Extrusion
3. Blow Molding
4. Compression Molding
5. SMC Compression Molding
6. Filament Winding
7. Pultrusion
8. Thermoplastic Foam Molding
9. Thermoforming
10. Reaction Injection Molding

Three of these models, injection molding, SMC molding, and filament winding, are described in detail in the following sections.

INJECTION MOLDING COST MODEL

Injection molding is a process for converting plastic pellets, flake, or regrind into finished molded products. Examples of injection molded products are ubiquitous. Approximately 32 percent by weight of all plastics are processed by injection molding, second in volume only to the extrusion process (4). In terms of numbers of different applications, injection molding far exceeds all other plastics fabrication processes in annual volume.

The process, as modeled in this thesis, is reciprocating screw injection molding, to distinguish it from other variations of injection molding. A simplified description of the mechanics of this process is as follows. Melted plastic material is injected into the cavity of a matched mold, where it cools and solidifies, assuming the shape of the cavity. Plastic is injected by the plunger action of a screw, acting as a piston within a closely fitted barrel or cylinder. As the screw advances, melted plastic is forced through a nozzle into the cavity of the mold. After injection, the screw rotates within this barrel and recedes slowly, forcing more plastic toward the nozzle in preparation for the next injection. The screw, barrel, and nozzle are hot, melting the plastic. The mold cavity is cool, causing solidification.

The injection molding model is organized on a spreadsheet as indicated in Figure 1 on page 42. The four major sections of this model are Inputs, Materials, Geometries, and Outputs. Each is described in the following sections.

INPUTS

The inputs to the injection molding technical cost model are divided into seven sections, as shown in Figure 1 on page 42. In a general sense, the inputs within each grouping correspond to the title of the group; for instance, "Tooling Cost Parameters" relate to the cost of tools. There is, however, an important functional difference between the groupings.

The first two sets of parameters, "Component Specifications" and "Other Inputs", must be supplied each time the cost of molding a component is estimated (except for four optional inputs, used to override internally estimated values). These data are constantly being changed on a case dependent basis. There is no meaningful concept of their industry average values or of their general correctness.

The "Exogenous Cost Factors" are input parameters that must be reviewed and updated periodically. These data reflect the economic environment being modeled, and they vary spatially and temporally. In a given economic environment, there is meaningful consideration of the accuracy or correctness of these data.

The next three groups of inputs, "Process Parameters", "Cycle Time Parameters", and "Tooling Cost Parameters", describe industry average practice or economics. These data are less likely to change than data from the other groups. They are also more difficult to adjust when it is necessary to change them, as many are obtained from regression analyses performed on

INPUTS	MATERIALS	GEOMETRIES	OUTPUTS
Component Specifications Other Inputs Exogenous Cost Factors Process Parameters Cycle Time Parameters Tooling Cost Parameters Currency Conversions			Variable Costs Fixed Costs Additional Info.

Figure 1. Injection Molding Model Layout

a wide range of case studies from industry at-large. Accurately changing these parameters generally involves extensive data collection and analysis.

The final grouping, "Currency Conversions", are data for converting the output into foreign currencies. These values change daily, but do not effect any of the technical or process related variables within the model. "Currency Conversions" are included for the convenience of those persons using the injection molding model outside of the United States.

A detailed discussion of the inputs, their meaning, and their sources, for the parameters in each grouping, is provided in the following sections. Discussion of the use of these parameters in estimating part costs is deferred until the section on the model outputs.

COMPONENT SPECIFICATIONS

Six parameters are used to specify the component for which the cost of injection molding is to be estimated. These inputs are:

1. Material - The "Material" is selected by number from a menu. The available choices are described in a later sections of this thesis.
2. Geometry - The "Geometry" is also selected by number from a menu.
3. Weight - This parameter is the weight in grams of a single finished component. As such, this value does not include the weight of sprues, runners, or other plastic material that is trimmed from the part prior to finishing. For multi-cavity molds, this is the weight of a single component from the mold. For family molds, it is the combined weight of the family of components. However, the data set presented in this thesis does not estimate the costs of molding families of components with good accuracy.
4. Maximum Wall Thickness - This input parameter is equal to twice the distance in millimeters from the point within the solid part that is farthest from the nearest wall to the nearest wall. When the molded part is cooling in the tool, this is twice the distance from the surface of the part to the point that cools most slowly.
5. Average Wall Thickness - This the average or nominal thickness of the walls of the part, measured in millimeters. For plastic parts with

constant wall thickness, this parameter is easily obtained. When the wall thickness varies, an estimate must be obtained.

6. Projected Area - This is a measure of the area of the silhouette of the component, when cast in the direction of mold parting. A light shined on the part in the direction that the mold separates projects a shadow that has an area equal to the projected area of the component.

Each "Component Specification" has an implied range of applicability since many of the parameters and equations within the model are derived from case studies. This range of applicability for the component weight is from 25 to 5000 grams; for the wall thickness, from 1.5 to 6 millimeters; and for projected area, from 20 to 6000 square centimeters. When specifications fall outside of these ranges, the model still estimates costs; however, these estimates are extrapolated, and their accuracy is less certain.

OTHER INPUTS

There are nine "Other Inputs" to the injection molding model. Out of these, four are optional and two are binary, involving yes/no decisions. The "Other Inputs" are:

1. Annual Production Volume - This parameter is the total number of components to be produced over the course of a production year. When the total annual production involves several short production runs, the

annual volume is the sum of these runs. However, in these situations, the model may not estimate costs accurately. Computing costs on the basis of the total annual production implicitly assumes that downtime associated with changing from one production run to another is not significant. For prototype molding or where production runs are less than about 5,000 units per year, the model may not accurately estimate costs.

2. Product Life - The "Product Life" is the number of years that the product will be produced before it is discontinued. "Product Life" defines the capital recovery period for recovering the investment in tooling, except in situations where tools physically wear out (see "Tooling Cost Parameters" on page 59).
3. Number of Cavities - This parameter is the number (1 to 16) of identical cavities in the tool, and is generally an even number.
4. Tool Actions - This binary (yes/no) input variable states whether or not the tool for molding the component contains tool actions. Tool actions are moving parts within the tool that are required when the component cannot be released in the direction of mold parting. Actions are required for undercuts, inserts, screw threads, and other design features which preclude the use of a simple split mold. The primary effect of tool actions is to raise the cost of tooling.
5. Dedicated Equipment - This binary input parameter is used to switch between two accounting assumptions, dedicated or non-dedicated equipment. Dedicated equipment assumes that the equipment is dedicated to

the production of only the one component, and that it is left idle once the production run is complete. Non-dedicated equipment assumes that the equipment is used to produce many components. The choice between dedicated and non-dedicated depends on the nature of the business being modeled and upon the time required for the production run.

6. Cycle Time <optional> - This is the first of four optional inputs, and if a non-zero value is specified, it will override the internally estimated cycle time value. If zero is entered, the model uses the internally estimated value described in "Total Cycle Time" on page 96. This option is available because the internal cycle time algorithm is not always accurate, and because it is often desirable to investigate the cost implications of changing the cycle time.

7. Tool Cost <optional> - This is the second optional input which allows an override of the internal estimate for tooling cost. Optional tool cost is entered in thousands of dollars. In situations where multiple sets of tools are required, only the cost of a single set of tools should be entered.

8. Cost of Shop Time <optional> - The cost of shop time is an optional input that changes the basis for cost estimation from the "technical cost method" to the "material plus shop time" method (see "Material Cost Plus Shop Time" on page 12). Values are entered in dollars per hour, and reflect the fully loaded cost of running the injection molding machine that is to be used to mold the part. When a non-zero value is entered, all of the cost elements except for materials, machines,

and tooling are not displayed since they are implicitly included in the cost of shop time.

9. Clamping Force <optional> - This is an optional input that specifies the machine clamping force in kilonewtons. The clamping force is specified when it is known that processing will involve a specific size machine. Otherwise, the model estimates optimal machine size and assumes processing will involve this equipment.

EXOGENOUS COST FACTORS

The "Exogenous Cost Factors" are variables that describe the economic environment of the injection molding business. The values for these parameters that are shown in Figure 2 on page 48 correspond to domestic industry averages. These values were obtained from trade societies, publications, and from interviews with molders, equipment suppliers, and material suppliers.

Each of these inputs will vary significantly by region and over time. They must be reviewed and adjusted regularly, especially when estimating costs for different molding businesses. A description of each of the exogenous cost factors is provided below.

1. Direct Wages - This parameter is the wage rate in dollars per hour paid to direct labor, including the cost of the benefits to the laborer.

Direct Wages (w/ benefits)	$12.00 /hr
Working Days/Yr	240
Working Hours/Day	16
Capital Recovery Rate	10%
Working Capital Period	3 months
Price, Building Space	$800 /sq m
Building Recovery Life	20 yrs
Price of Electricity	$0.080 /kWh

Figure 2. Exogenous Cost Factor Inputs

The average wage is about $12/hr, but can vary from $5/hr to $25/hr depending on the molding business (5).

Labor benefits include the costs of health insurance, retirement plans, and other employee incentives that directly benefit the laborer. Benefits do not include overhead costs such as utilities, land, supervisory labor, etc., as these elements of cost are accounted separately in the technical cost method.

2. Working Days/Year and Working Hours/Day - These parameters specify the length of the working year and day, respectively. Average values for the domestic molding industry are 240 days/year and 16 hours/day, although it is not uncommon to run a molding business 24 hours/day.
3. Capital Recovery Rate - This parameter specifies the interest rate for capital recovery. It can also be considered to be the return on investment for the capital investments in machinery, tooling, buildings, etc. The industry average value for this parameter is difficult to establish. However, it is reasonable to assume that the

average capital recovery rate is slightly higher than the prime lending rate of major banks.

4. Working Capital Period - This is the average length of time in months that capital is tied up in material inventories and payrolls. Working capital is treated like any other capital investment and charged for the time value of money. Reducing the working capital period is equivalent to turning-over inventories more rapidly, and leads to a reduction in cost. The cost implications of inventories are not fully captured by this parameter.

5. Price, Building Space - This parameter is the average price in dollars per square meter of factory floor space. The default value is $800/sqare meter (6); however, actual values vary considerably from region to region.

6. Building Recovery Life - The "Building Recovery Life" is the number of years over which the capital investment in factory buildings is recovered. This parameter is often confused with the depreciation period, which is the length of time over which an investment is written down as a tax deduction. The capital recovery period is set to be roughly equal to the productive life of the investment; the depreciation period is mandated by tax law.

7. Price of Electricity - This parameter is the price in dollars per kilowatt-hour of electric energy. Values for this parameter typically vary from $0.006/kWh to $0.130/kWh, depending on the region and level of consumption.

PROCESS PARAMETERS

The "Process Parameters" describe the unique physics and economics of injection molding. The values for these parameters presented in Figure 3 on page 51 are industry averages. In actual case studies, these values can vary for many reasons. The "Process Parameters" and the factors effecting them are described in the following list.

1. Machine Cost Intercept and Slope - These parameters are the regression constant and coefficient, respectively, from a regression analysis relating machine investment cost to machine clamping force. These parameters are used within the model to estimate the machine investment, given either the internally estimated or the optional override value for clamping force. Data for these regressions came from Battenfeld (7), and these data, as well as the statistics from the analysis, are presented in Appendix A.
2. Recovery Period of Machine - This parameter is the number of years over which the capital investment in the injection molding machine is recovered. This parameter is similar to, but not synonymous with, the depreciation period for capital equipment. The difference between these two is that the capital recovery period is set by an independent decision of the molder, whereas depreciation periods are set by tax codes.

Machine Cost Intercept	$14,829
Machine Cost Slope	$41 /kN
Recovery Period of Machine	6 yrs
Direct Laborers Per Machine	1
Mold Pressure Intercept	172 bars
Mold Pressure Slope	224 rt.cm/psi
Auxiliary Equip. Cost (% mmch)	20.0%
Installation Cost (% mmch)	20.0%
Overhead Burden (% fc)	35.0%
Maintenance Cost (% fc)	4.2%
Productive Time (% total time)	85.0%
Material Scrap Rate (%)	2.0%
Electricity Requirement	0.75 kWh/kg
Floor Space Coefficient	135 sq m
Floor Space Scaling Exponent	0.71

Figure 3. Process Parameter Inputs

The default value for the capital recovery period is six years. This value was established through discussion with custom molders. It does not reflect the average physical life of an injection molding machine which typically is at least 12 years. On a strict cost basis, the physical life of the machine (12 years) should be the basis for capital recovery. However, it is standard practice for custom molders to recover capital investments in an accelerated time frame.

3. Direct Laborers per Machine - The number of laborers per machine is the number of persons directly associated with injection molding the specified component. This parameter is given the default value of one; however, it can range from a fraction of a laborer, usually no lower than one third, up to three laborers per machine. Fractional laborers

reflect the situation where one person is running more than one molding machine.

The number of direct laborers is not limited to the operators. If additional labor is required to place inserts into the mold, or to transport or trim the component directly after molding, these persons are considered direct laborers, and should be accounted.

The widespread use of picker/placer robots may reduce the average number of direct laborers per machine in the future. However, at present, many injection molding businesses that use robots still need laborers to monitor them. Consequently, there has been little reduction in the labor content.

4. Mold Pressure Intercept and Slope - These input parameters are used to estimate the maximum average pressure within the mold during injection. They are used in an equation along with the projected area and average wall thickness to estimate the minimum clamping force of the molding press. The relationship between wall thickness and mold pressure as modeled by these parameters is shown in Figure 4 on page 53. Data for this relation were obtained from DSM (8) for their Stamylan P polypropylenes. The validity of this relationship for other resins, particularly heavily filled materials, is questionable.

   Theory suggests that the relationship defining average internal mold pressure is more complicated than indicated by Figure 4 on page 53. Other factors, including the flow path length, melt viscosity, processing temperatures, and geometry, also effect internal pressure.

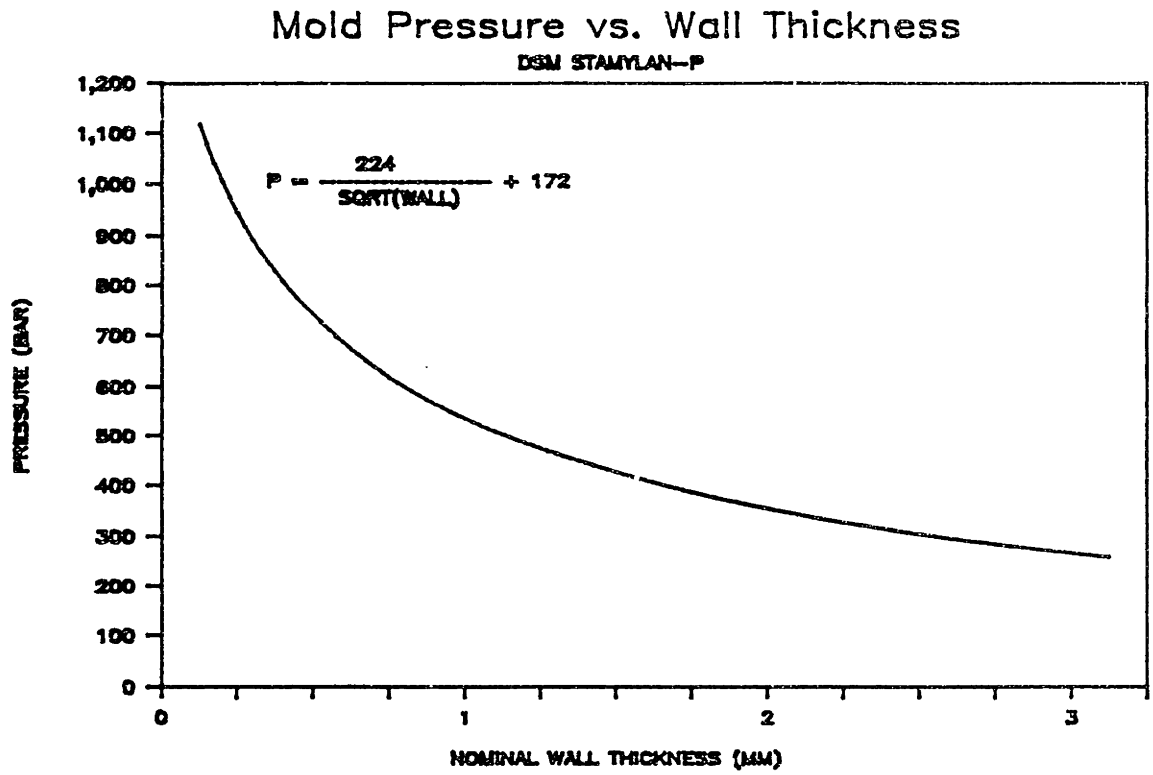

Figure 4. Internal Mold Pressure vs. Wall Thickness: DSM Stamylan P

However, in practice, these parameters are not accurately known, and empirical rather than theoretical solutions are employed.

The form of the pressure vs. wall thickness equation cannot be explained easily with simple transport theory. For isothermal Poiseuille flow of Newtonian fluids between parallel plates, theory states that to maintain constant volumetric flow rate, pressure must vary inversely with the cube of the distance separating the plates (9). The same theory indicates that for constant average fluid velocity, pressure must vary inversely with the square of the distance between the plates. The relationship presented in Figure 4 indicates that

internal molding pressure varies inversely with the square root of the wall thickness.

Qualitatively, one would expect that the pressure required to fill a cavity would decrease with increasing nominal wall thickness, since pressure losses along the flow path decrease as the walls are moved farther apart. That this decrease should be inversely proportional to a higher power of wall thickness seems unlikely; while the effect of wall thickness is strong, it is certainly not overwhelming.

5. Auxiliary & Installation Costs - The cost of auxiliary equipment and the cost of installing all equipment is estimated as a percentage of the investment in the main machine. The default value for both of these percentages is 20 percent. This value corresponds more to standard practice in cost estimation than to a known industry average. The range over which these parameters vary in practice is probably from less than 10% to more than 100%.

6. Overhead Burden - The cost of fixed overhead, including engineering and supervisory labor and fixed expenses not accounted as line-items, are estimated as a percentage of other fixed costs. The default value of 35% has been reviewed with cost estimators (10), but has not been directly estimated from citable data. The expected range for this parameter is from 20% up to more than 100%. Precise data on fixed overhead burden are extremely difficult to collect.

Overhead burden is often confused with variable burden, an economic instrument described in "Material Cost Plus Loaded Shop Time" on

page 13 of this thesis. Variable burden is a "catch-all" parameter, used to estimate all fixed costs from direct labor wages. Overhead burden, as applied in this model, accounts for only those elements of fixed cost not estimated separately. The distinction between fixed and variable burden will become more apparent in the section detailing the cost estimation equations.

7. Maintenance Cost - The cost of maintaining equipment and tooling is estimated as a percentage of the total cost of these investments. The default value specified in the injection molding model is 4.2%. However, maintenance costs are a complex function of the type and age of the equipment, the complexity of the tooling, and the design of the component being molded, and can vary from this default value, significantly.

8. Productive Time - This parameter defines the fraction of available time that both the equipment and labor are producing good components. The default value of 85% was obtained from the Society of the Plastics Industry (11), and is an average for domestic custom injection molding businesses. Discussions with European molders (12, 13) indicate this value is also appropriate for Europe, although the amount of available time in a working year is often less. The range over which this parameter was found to vary is from 75% up to 95%, depending on the business.

9. Material Scrap Rate - This parameter measures the difference between the amount of material purchased for a production run and the amount that actually ends up as molded product. The default value of 2%

scrapage is standard for molding melt reprocessable thermoplastics. Heat sensitive, or contamination sensitive materials cause the scrap rate to increase. The injection molding cost model addresses this feature through the application of a "Process Multiplier", described in the following section on "Materials".

The scrap rate, as defined, does not relate to the difference between the shot weight (the total weight of material injected in one cycle) and the finished weight of the molded part(s). This distinction is often misunderstood. Runners, sprues, gates, or other portions of the molding that are part of the shot weight, but that are trimmed from the part and reprocessed, do not constitute scrap.

10. Electricity Requirement - This parameter is used to estimate the amount of electricity consumed by the injection molding machine and auxiliary equipment (including chillers and dryers) in processing one kilogram of material. The default value of 0.75 kWh/kg is the amount of heat required to raise the temperature of polystyrene from room temperature (20C) to melt temperature (204C), assuming an overall efficiency of 10%. For materials other than polystyrene, the electricity requirement is automatically adjusted, accounting for differences in the heat capacity and melt temperature.

11. Floor Space Coefficient and Exponent - These parameters are used to estimate the number of square feet of building space required for the molding operation, including space for the molding machine, auxiliary equipment, material storage, and parts warehousing. Values for these

parameters were originally obtained from a study of the economics of injection molding (14), but were later modified through the analysis of case studies.

CYCLE TIME PARAMETERS

The cycle time parameters are used to estimate cycle time, defined as the number of seconds that elapse between consecutive closings of the mold. Their values were established through a combination of theory and regression analysis, and they have been validated through comparison with case studies. The cycle time equation is presented in "Total Cycle Time" on page 96. This equation estimates cycle time from the kinetics of cooling and from the size of the component.

Thirty-one case studies were used as data for the regression analysis. Both the raw data and the correlation statistics are provided in Appendix B. The range of cycle times in molding these components is from 5.9 seconds to 120 seconds. These components are molded from 11 different classes of polymers, namely:

1. High Density Polyethylene (HDPE)
2. Low Density Polyethylene (LDPE)
3. Acrylonitrile-Butadiene-Styrene (ABS)
4. Polypropylene (PP)
5. High Impact Polystyrene (HIPS)
6. Polyamide (PA; nylon)
7. Polyethylene Sulfide (PES)
8. Polycarbonate (PC)
9. Styrene-Acrylonitrile (SAN)

10. Polyvinyl Chloride (PVC)
11. Polyacetal

The range of weight for these components is from 4.6 grams to 1755 grams; projected areas range from 6 square centimeters to 4000 square centimeters.

The range of values for the case study data defines the statistically significant range of the derived cycle time equation. Outside of this range, the cycle time equation provides estimates that are less certain. However, even when the equation is used outside of these ranges, particularly when it is used for materials not included in the list, the estimates are acceptable, usually within 20% of known values.

Even though the cycle time equation has general applicability, it does not model the process whereby cycle time is established. In practice, cycle time is determined subjectively. Cycle times are established by begining excessively long, then shortening the cycle until the ejected component warps on ejection. Requirements for good surface finish or close dimensional tolerance lengthen the cycle time, but not in an analytically predictable manner.

The injection molding cost model has been structured to permit manual overriding of the cycle time estimate. Also, this feature can be used to perform an analysis of the sensitivity of costs to changes in cycle time.

TOOLING COST PARAMETERS

The "weight", "area", and "action factors", and the "constant" and "toolmaker shop rate" are parameters used to estimate the cost of a set of tools for molding the specified component. These parameters were established from regression analysis, using the same data set described in the preceding section on cycle time. The tooling cost equation is presented in "Tooling Cost" on page 80.

The "baseline mold life" parameter is the number of times that the tools can be cycled before physically wearing out. The default value for this parameter is one million. While it is often possible to maintain a set of tools indefinitely, after one million cycles the cumulative expense of maintenance is often approximately equal to the cost of a replacement tool set.

Often, tooling is retired from service before it has been used to mold one million components. This occurs when the product being molded becomes obsolete, or when it is replaced by a model revision. In these situations, the "length of production run" parameter establishes the economic life of the tools, rather than the physical number of cycles. Changing from the physical life basis to the product life basis is handled automatically by the model.

CURRENCY CONVERSIONS

The currency conversion parameters are shown in Figure 5 on page 61. These input parameters are used to convert the cost estimate from US dollars into international currencies. A currency is selected by inputting its number into the cell labled "Currency <menu>". Below this cell, a menu of currencies and their approximate conversion rates appears. These rates can be changed, as they fluctuate daily.

SUMMARY OF INPUTS

The inputs to the injection molding cost model form the basis for cost estimation. They define the component, the economic environment, and the technical nature of the injection molding process. The default values for these inputs (except for the component specification inputs) are indicative of industry averages.

However, each parameter can reasonably be expected to vary over a wide range; the default values provide average general accuracy. The input parameters define the cost of molding a component. The procedure for estimating costs can be reduced to estimating these parameters. If they are estimated accurately, so is the cost of the component.

Currency	1 <menu>	
Menu	#	/$US
US Dollars	1	1.00
Deutsche Marks	2	2.17
Swiss Francs	3	1.82
Italian Lire	4	1489.00
Austrian Shillings	5	15.28
Dutch Guilders	6	2.46
Japanese Yen	7	175

Figure 5. Currency Conversion Factors

MATERIALS

The choice of the material directly effects the cost of the molded part. Each raw material is purchased for a price, and this price establishes the contribution of direct material cost to the total. In addition, the choice of the material also effects processing parameters like the cycle time, the life of the equipment, and the energy requirements.

The injection molding cost model captures the influence of the material selection with data contained in a materials database. This database is shown in Figure 6 on page 62, and its contents are described in the following sections.

There are five general types of data contained within the database, namely: 1) Material Descriptions, 2) Material Prices, 3) Processing Multipliers, 4) Processing Conditions, and 5) Material Properties. Most of these data were obtained from material suppliers and plastics processors.

MATERIAL DEPENDENT FACTORS

Type	Tradename	Grade	#	Price ($/kg)	XML	XSC	XAU	XMA	Temp Melt	Temp Tool	Temp Eject	k (W/mK)	Cp (J/kgK)	Specific Gravity
POLYSTYRENE			1	$2.33	1.00	1.00	1.00	1.00	204	35	70	0.13	1340	1.050
PVC (RIGID)			2	$0.84	0.80	1.00	1.00	1.00	177	35	65	0.18	1400	1.350
ABS			3	$2.22	1.00	1.00	1.10	1.00	246	35	70	0.25	1500	1.050
POLYPROPYLENE (HOMO)			4	$0.97	1.05	1.00	1.00	1.00	246	35	65	0.12	1925	0.900
NYLON 6			5	$4.38	1.00	1.00	1.30	1.10	260	45	80	0.24	1675	1.130
POLYCARBONATE			6	$3.96	0.85	1.00	1.20	1.10	282	55	80	0.20	1260	1.200
ACETAL (HOMO)			7	$3.43	0.90	1.10	1.20	1.00	218	45	80	0.23	1470	1.400
HDPE			8	$0.81	1.00	1.00	1.00	1.00	218	35	55	0.48	2300	0.950
POLYPHENYLENE ETHER			9	$2.93	0.98	1.00	1.20	1.00	274	45	75	0.19	1340	1.080
PET			10	$3.52	0.90	1.20	1.30	1.05	302	45	80	0.15	1715	1.370
THERMOPLASTIC POLYIMIDE			11	$11.88	1.00	1.11	1.30	1.00	343	65	100	0.10		1.400
EVA			12	$2.09	1.05	1.00	1.00	1.00	163	30	50	0.38	2300	0.920
NYLON 6/30% GLASS			13	$4.27	1.00	1.10	1.30	1.30	271	45	85	0.24	1255	1.380
POLYCARBONATE/30% GLASS			14	$5.21	0.75	1.25	1.30	1.30	316	55	90	0.22		1.400
ABS/20% GLASS			15	$2.38	0.80	1.11	1.20	1.30	218	35	80	0.27		1.220
ACETAL/25% GLASS			16	$4.07	0.80	1.10	1.20	1.25	221	45	85	0.25		1.610
PBT Alloy	Valox	830	17	$3.26	0.85	1.00	1.30	1.30	254	80	120	0.29		1.540
PC/PBT	Xenoy	1200	18	$3.96	1.00	1.00	1.30	1.00						1.200
PC/PBT	Xenoy	1101	19	$3.74	1.00	1.00	1.30	1.00						1.210
PC	Lexan	141	20	$4.64	1.00	1.00	1.30	1.10	300	93	110	0.19	1250	1.200
PPE	Noryl	844	21	$2.66	1.00	1.00	1.20	1.00	274	45	75	0.19		1.060
PA	Zytel	ST-801	22	$5.06	1.00	1.00	1.30	1.30						
PA	Zytel	ST-901	23	$5.41	1.00	1.00	1.30	1.30						
EVA Co-	Elvax	960	24	$1.50	1.10	1.00	1.00	1.00						
PA	Bexloy		25	$4.07	1.00	1.00	1.30	1.30						
PA	Bexloy		26	$4.40	1.00	1.00	1.30	1.30						
Ionomer	Surlyn		27	$2.97	1.05	1.00	1.00	1.00						
LDPE	Stamylan-LD	2138GW00	28	$0.73	1.20	1.00	1.00	1.00	180	40	50	0.32	2300	0.921
LDPE	Stamylan-LD	2322GL00	29	$0.73	1.20	1.00	1.00	1.00	180	40	50	0.32	2300	0.923
LDPE	Stamylan-LD	2538EL00	30	$0.73	1.20	1.00	1.00	1.00	180	40	50	0.32	2300	0.925
HDPE	Stamylan-HD	7249	31	$0.81	1.20	1.00	1.00	1.00	200	40	70		2300	0.952
HDPE	Stamylan-HD	7058	32	$0.81	1.20	1.00	1.00	1.00	240	40	70		2300	0.952
HDPE	Stamylan-HD	5119	33	$0.81	1.20	1.00	1.00	1.00	200	40	60		2300	0.943
PP Co-	Stamylan-P	83MF10	34	$0.93	1.20	1.00	1.00	1.00	260	40	78	0.22	1680	0.905
PP Co-	Stamylan-P	412MN40	35	$0.67	1.20	1.00	1.00	1.00	210	40	88	0.22	1680	0.905
PP Co-	Stamylan-P	48M10	36	$0.87	1.20	1.00	1.00	1.00	220	40	88	0.22	1680	0.905
EMPP	Keltran TP	0603	37	$1.83	1.20	1.00	1.00	1.00	240	35	70	0.22	2000	0.895
EMPP	Keltan TP	0505	38	$1.93	1.20	1.00	1.00	1.00	240	35	70	0.22	2800	0.890
EMPP	Keltan TP	2607	39	$1.73	1.10	1.00	1.00	1.00	240	35	70	0.24	2400	1.050
R-EMPP	Kelburon	90594	40	$1.89	1.20	1.00	1.00	1.00	240	35	70	0.22	2000	0.900
ABS	Ronfalin	FX	41	$2.13	1.00	1.00	1.00	1.00	220	40	90	0.25	1500	1.060
ABS	Ronfalin	TX	42	$2 24	1.00	1.00	1.00	1.00	240	50	94	0.25	1500	1.060
ABS	Ronfalin	HX	43	$2.24	1.00	1.00	1.00	1.00	265	60	105	0.25	1500	1.060
ABS	Ronfalin	VE	44	$2.72	1.00	1.25	1.00	1.10	230	50	85	0.25	1500	1.280
ABS/PVC	Ronfalin	RN-03	45	$2.64	1.00	1.25	1.00	1.20	210	50	78	0.22	1450	1.260
PPE	Prevex	PNA	46	$3.43	1.00	1.00	1.20	1.00	275	77	95	0.19	1340	1.060
PPE	Prevex	PQA	47	$4.29	1.00	1.00	1.20	1.00	290	100	115	0.19	1340	1.060
PPE	Prevex	VJA	48	$3.75	1.00	1.00	1.20	1.00	265	70	95	0.19	1340	1.100
PPE	Prevex	W30	49	$3.76	1.00	1.00	1.20	1.00	275	77	95	0.19	1340	1.060
ABS	Cycolac	T	50	$2.50	1.00	1.00	1.10	1.00	246	52	85	0.25	1500	1.040
ABS	Cycolac	GSM	51	$2.53	1.00	1.00	1.10	1.00	246	52	85	0.25	1500	1.040
ABS	Cycolac	L	52	$2.60	1.00	1.00	1.10	1.00	250	52	85	0.25	1500	1.020
ABS	Cycolac	DFAR	53	$2.35	1.00	1.00	1.10	1.00	242	52	85	0.25	1500	1.040
ABS	Cycolac	DH	54	$2.42	1.00	1.00	1.10	1.00	246	71	90	0.25	1500	1.050
ABS	Cycolac	KJB	55	$2.99	1.00	1.00	1.10	1.00	223	63	85	0.25	1500	1.220

Figure 5. Materials Database

For the "generic" materials, data were taken from handbooks and other literature sources.

A total of 55 materials are contained within the current database. Of these, the first 16 are "generic" materials, not associated with a specific manufacturer. Generic materials are hypothetical and should be selected cautiously, because within each generic material class, a wide range of price and properties exists. For instance, the bulk price of different grades of ABS from one supplier ranges from $2.22 to $4.18 per kilogram (15). The price of generic ABS in the materials database is $2.22/kg.

It is usually preferable to select specific tradenames and grades of materials, since their prices and properties can be verified. Thirty-nine of the materials within the database are specific grades.

MATERIAL DESCRIPTIONS

Except for the "generic" materials, each material description consists of the base polymer type (e.g., LDPE, PS, PP), the manufacturer's tradename, and the specific grade of interest. The "generic" materials are defined by the polymer type and whether or not the material is reinforced. Additionally, each material is numbered, and this number is the input parameter by which the material is selected.

MATERIAL PRICES

The price in dollars per kilogram is the first numeric entry within the database. Except for the generic materials, this price corresponds to the manufacturer's bulk list price, taken from published price sheets. Bulk prices are given for purchases of truck-load quantities, and a premium must be paid if smaller quantities are purchased.

Two facts obscure the accuracy and reliability of the price data. First, list prices are subject to frequent changes. Second, list prices may not be the same as market transaction prices, since discounts on the order of 20% are often awarded by the suppliers to stimulate sales. Because of these factors, the price values for specific manufacturer's grades should be thought of as estimates of the actual values.

For the generic materials, prices were taken from trade journals (16). The accuracy of these data is unknown.

MATERIAL MULTIPLIERS

Multipliers are used to capture the influence of the material selection on the following variables:

1. The physical life of the equipment and tooling (XML),
2. The material scrap rate (XSC),
3. The auxiliary equipment requirement and cost (XAU), and
4. The investment in equipment and tooling (XMA).

For each material, values for these multipliers are contained within the database. Multipliers are estimated as ratios relative to the baseline material, generic polystyrene (therefore, the multipliers for polystyrene are all equal to 1.00). The equations for estimating these parameters are presented in Figure 7 on page 66. However, it is somewhat misleading to represent these as analytical expressions, since their values are subjective, and were determined through questionnaires administered to plastics molders. The following list discusses some considerations that were involved in establishing the material multipliers.

1. XML - The physical life of the equipment and tooling is effected by the abrasiveness and/or corrosiveness of the material being processed. Plastics that are filled with chopped glass fiber are usually abrasive. Screws, barrels, nozzles, sprues, gates, etc. wear more rapidly when processing these materials, and equipment life is shortened. The XML factor for glass reinforced materials is less than 1.00, indicating that processing these materials shortens the equipment life.

   Corrosive materials also reduce the life of equipment. Polyvinylchloride, which de-hydrohalogenates during processing releasing hydrochloric acid, is the prime example of a corrosive material. The XML factor for PVC based plastics is estimated to be 0.80, indicating that equipment life is 20% less when processing these materials than for general purpose polystyrene.

$$XML = \frac{\text{Equipment Life Using the Material}}{\text{Equipment Life Using Polystyrene}}$$

$$XSC = \frac{\text{Scrap Rate of the Material}}{\text{Scrap Rate of Polystyrene}}$$

$$XAU = \frac{\text{Cost of Auxiliary Equipment to Process the Material}}{\text{Cost of Auxiliary Equipment to Process Polystyrene}}$$

$$XMA = \frac{\text{Cost of Equipment Needed to Process the Material}}{\text{Cost of Equipment Needed to Process Polystyrene}}$$

Figure 7. Estimation of Material Multipliers

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2. XSC - The choice of material can effect the scrap rate for two reasons. First, some materials are sensitive to re-processing; for instance, PET and polyacetals. For these materials, the sprues, runners, and other trimmings cannot always be re-ground, and scrappage increases correspondingly.

   Other materials (e.g., optical grades of polycarbonate) have high scrap rates because of their susceptability to contamination.

3. XAU - The choice of material can effect the requirement for auxiliary equipment. For instance, compared with general purpose polystyrene, most engineering thermoplastics require additional care in handling and drying. Thus, these materials have XAU values ranging from 1.20 to 1.30, as shown in Figure 6 on page 62.

4. XMA - The choice of material also effects the investment in equipment and tooling. Abrasive or corrosive materials are typically processed with more expensive equipment, as are materials which melt at extremely high temperatures. The added investment required to process these materials is for bimetallic barrels, chrome-plated or nitrided screws, surface treated tooling, etc.

PROCESSING CONDITIONS

Three process temperatures are included within the material database for each material. These are:

1. Melt Temperature
2. Tool Surface Temperature
3. Part Ejection Temperature

Values for these data are obtained from resin suppliers and from case studies. Melt temperature is defined as the average temperature of the molten plastic as it enters the tool. Tool surface temperature is the average temperature of the surface of the tool, averaged over one full mold cycle and over all of the tool's surface area. Part ejection temperature is the average temperature of the molded part as it is ejected from the tool.

Values of these temperature parameters are, at best, approximations of typical molding conditions. In practice, these data are difficult or impossible to measure precisely. Process temperatures are used to estimate

the cycle time and energy consumption. Uncertainty regarding the accuracy of a temperature value is best addressed by examining the estimated cycle time and energy consumption, directly.

MATERIAL PROPERTIES

Three physical properties of each material are included within the materials database, namely:

1. k (W/mK) - the thermal conductivity
2. Cp (J/kgK) - the heat capacity
3. specific gravity

These material properties are used in the estimation of the cycle time, energy consumption, and part complexity factor. The equations for estimating each of these elements are presented in a later section of this thesis. Uncertainty regarding the value of a material property can be addressed by perfoming a sensitivity analysis on that property, as described in "Injection Molding Sensitivity Analysis" on page 104.

While each of these properties varies depending upon the temperature at which it is measured, these variations are not taken into account by the model. Rather, the tabulated value for each property shown in Figure 6 on page 62 corresponds to the temperature intermediate between the melt and ejection temperatures.

SUMMARY OF THE MATERIALS DATABASE

The injection molding cost model accounts for the effects of material selection on the costs of a molded part with the data contained in the materials database. As of this writing, there are 16 generic and 39 tradename materials to select from contained within the database, and room for a total of 100. To incorporate a new material, the parameters described above must be collected, estimated, or measured, and entered along with the designation of the material.

Records in the database effect many aspects of the estimated part cost. The equations presented in upcoming sections detail these effects. Uncertainty regarding the value of a material data parameter can be addressed by sensitivity analysis, as described later in this thesis.

GEOMETRIES

As modeled, the geometry of a component effects four aspects of the cost of molding that component, namely:

1. The cost of the tooling (YMO),
2. The material scrap rate (YSC),
3. The cycle time (YCY), and
4. The life of the tooling (YML).

The effects of geometry on cost are accounted for within the geometries database, similar to the materials data base described above. Specifically, the geometries database contains four parameter multipliers,

and uses these to account for cost differences that arise directly from the selection of part geometry. The geometries database is presented in Figure 8 on page 71.

As shown, there are 10 generic geometries contained within the current database. Each has associated with it four multiplier parameters, and all of these multipliers have default values of 1.00. As presented, the selection of a geometry has no effect on the cost of molding a component.

The concept of geometry adjustment factors is sound. However, in practice, it is impossible to account for the influence of geometry by this approach. Two factors preclude the use of a generalized geometries database. First, it is impossible to produce a simple but comprehensive list of molded part shapes. Second, even with identifiable shapes, it is impossible to define them in other than subjective terms or by lists of examples. Utilizing generic geometry lists sacrifices some of the objectivity of the technical cost modeling methodology.

The geometries database can be made useful by tailoring it to specific product shape categories. For instance, within the automotive industry, products such as fenders, instrument panels, etc. can be identified as product geometry shapes. The database can then be used as an added degree of freedom in accounting for cost differences between product groups.

Name	#	YMO	YSC	YCY	YML
SIMPLE CURVED PANELS	1	1.00	1.00	1.00	1.00
COMPLEX CURVED PANELS	2	1.00	1.00	1.00	1.00
OPEN BOX BEAMS (STRAIGHT)	3	1.00	1.00	1.00	1.00
SOLID COLUMNS (STRAIGHT)	4	1.00	1.00	1.00	1.00
OPEN BOX BEAMS (CURVED)	5	1.00	1.00	1.00	1.00
SOLID COLUMNS (CURVED)	6	1.00	1.00	1.00	1.00
COILS	7	1.00	1.00	1.00	1.00
OPEN BOXES	8	1.00	1.00	1.00	1.00
COMPLEX SOLID FLAT SURFACES	9	1.00	1.00	1.00	1.00
COMPLEX SOLIDS (CASTINGS)	10	1.00	1.00	1.00	1.00

Figure 8. Geometries Database

COST CALCULATIONS

Data from the inputs, materials, and geometries sections of the model are combined by a series of equations to produce a cost estimate, and these equations are described in detail in this section. Throughout this section, the numeric results that are provided are taken from a case study; the cost of producing a 5-liter trash bin equivalent to Rubbermaid's® Model 2845 (17). The complete cost estimate from this case study is presented in Figure 9 on page 72.

Like the model input section, the outputs are divided into parts: "Variable Cost Elements", "Fixed Cost Elements", and "Additional Information". These are discussed separately in the following sections.

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.75	$300,149	55.9%
Utility Cost	$0.10	$39,547	7.4%
Direct Labor Cost	$0.14	$57,761	10.8%
TOTAL VARIABLE COST ===>	$0.99	$397,458	74.1%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.08	$30,555	5.7%	$110,000
Tooling Cost	$0.05	$21,678	4.0%	$43,356
Overhead Labor Cost	$0.06	$25,987	4.8%	
Building Cost	$0.02	$7,047	1.3%	$140,936
Installation Cost	$0.02	$6,111	1.1%	$22,000
Auxiliary Equipment Cost	$0.02	$6,111	1.1%	$22,000
Maintenance Cost	$0.01	$2,746	0.5%	
Cost of Capital	$0.10	$38,880	7.2%	
TOTAL FIXED COST ===>	$0.35	$139,116	25.9%	$338,291
TOTAL FABRICATION COST ===>	$1.34	$536,574	100%	

ADDITIONAL INFORMATION	COSTS IN: $	
Raw Material Price	$0.73 /kg	$0.33 /lb
Scrap Rate (%)	2.0%	
Est. Total Ext. Surface Area	4537 sq cm	703 sq in
Mold Complexity Factor	6.26	
Energy Adjustment Factor	1.64	
Productive Mold Life	4.00 yrs	
Clamping Force	2,295 kN	258 tons
Cooling Time	8.8 sec	
Total Cycle Time	36.8 sec	
Cost of Shop Time	$52.49 /hour	
Run-Time for One Machine	125%	
Number of Parallel Streams	2.00	
Required Building Space	176 sq m	1896 sq ft
Currency Conversion Factor	1.00	

Figure 9. Injection Molding Model Output: Rubbermaid 2845 Trash Bin

VARIABLE COST ELEMENTS

Of the two sets of cost elements, the "Variable Cost Elements" can be calculated more easily, because the only estimated process variable that enters directly into their estimation is the cycle time. Otherwise, the variable elements are determined directly from input parameters and from engineering principles.

There are three "Variable Cost Elements" accounted for within the model. These are material cost, utility or energy cost, and direct labor cost. Each is discussed separately.

MATERIAL COST

The material cost is based upon four input parameters: material number, geometry number, weight, and scrap rate. The equation for estimating material cost is:

$$\text{Material Cost} = \frac{\text{Weight} * \text{Price}}{(1 - \text{Scrap Rate}) * \text{XSC(Material)} * \text{YSC(Geometry)}}$$

Selecting the material from the menu (in the case study, material number 29, DSM's low density polyethylene: Stamylan-LD 2322GL00 (18)) specifies values for both the price and the first scrap multiplier (XSC). The geometry selected from the geometries database establishes the second scrap multiplier (YSC).

The material cost equation yields results that are on the basis of cost per piece; $0.75 per trash bin in the case study. The estimated annual cost ($/yr) is obtained by multiplying the piece cost by the annual production volume, 400,000/yr, resulting in an annual cost of $300,149.

UTILITY COST

In the model, utility cost depends upon five factors: part weight, material number, electricity requirement, price of electricity, and energy adjustment factor. These factors yield utility cost as follows:

Utility Cost = Weight * Elec_Req * Elec_Price * EAF(material)

Elec_Req: electricity requirement (kWh/kg)
Elec_Price: electricity price ($/kWh)
EAF(material): energy adjustment factor, a funtion of the material (see "Additional Information" on page 89)

The model assumes that utility costs arise from the energy required to melt and plasticate the feed, leading to a linear relationship between piece weight and energy requirements. The mechanical energy required to operate the injection press is generally less than the energy required for heat, justifying this assumption (19).

The utility cost equation provides results on the basis of cost per piece, and for the case study, this amounts to $0.10. The annual cost estimate is obtained by multiplying piece cost by annual production volume.

DIRECT LABOR COST

The direct labor cost is computed based upon five parameters: cycle time, labor wages, labor requirements, labor productivity, and number of cavities in the tool. Of these, labor wages, requirements, and productivity, and the number of cavities in the tool are input parameters. Estimation of cycle time is discussed in "Total Cycle Time" on page 96. These factors are combined to estimate direct labor costs according to the following equation:

$$\text{Labor Cost} = \frac{\text{Cycle Time} * \text{Wage} * \text{Number of Laborers}}{\text{Productivity} * \text{Number of Cavities}}$$

The model assumes a simple linear relationship between labor cost and the five parameters. However, each of these parameters has a range of values over which it can vary, and the correct values for each parameter are often interrelated. For instance, both the number of cavities and the number of laborers may effect the productivity. Each input parameter should be examined to verify its appropriateness to the case study at hand.

As with the other variable cost elements, the equation provided above yields an estimate of the direct labor cost on the basis of cost per piece. In the case study, the cost of direct labor was $0.14 per trash bin, or 11% of the total.

FIXED COST ELEMENTS

Estimation of the fixed cost elements depends far more critically on computed process variables than did the estimation of variable cost elements. In part, this is a consequence of the interaction between cycle time, available process time, and annual production volume, that yields the required minimum number of parallel production streams. In this section, the number of process streams is taken as given, as was the cycle time in the section above. The calculation of the number of production streams is described in the "Number of Parallel Streams" on page 100.

Many of the fixed costs are estimated by relationships that reflect industry averages. This aspect may obscure the reasoning behind their estimation, as some of these relationships are strictly empirical. Verification of these relationships depends strictly upon evaluating the accuracy of the results.

Eight fixed cost elements are estimated in the injection molding cost model; each of these is described in the following section.

MAIN MACHINE COST

The model takes advantage of the fact that a strong correlation can be made between the cost and the clamping force of the machine. This concept is intuitively compelling, recognizing that bigger machines are more expensive. Through statistical analysis, it was found that the capital

investment in an injection molding machine can be estimated by the following equation. The raw data and regression statistics for this equation are provided in Appendix A, and the data are displayed graphically in Figure 10 on page 78.

Machine Investment = ($41 * Clamp Force + $14,829) * XMA(material)

Clamp Force - maximum clamping force in kilonewtons
$41 ($/kN) - Machine Cost Slope (See input parameters)
$14,829 - Machine Cost Intercept

In this equation, the clamping force determines the capital required to purchase one basic machine. This estimate is adjusted by the machine cost multiplier for the selected material (XMA), taking into account the fact that certain materials are processed on other than basic equipment. As with other equations using material multipliers, the baseline or unmodified equation is appropriate for modeling the cost of components made from general purpose polystyrene or from materials similar in processability to polystyrene.

The capital investment for a single machine is multiplied by the number of parallel machines required for the specified annual production volume. This investment is distributed over an estimated equipment life to yield annual cost, then over the annual production volume to yield piece cost.

The equipment life of the basic injection molding machine processing general purpose polystyrene is specified by the input parameter, "recovery period of the machine". The "recovery period of the machine" is multiplied

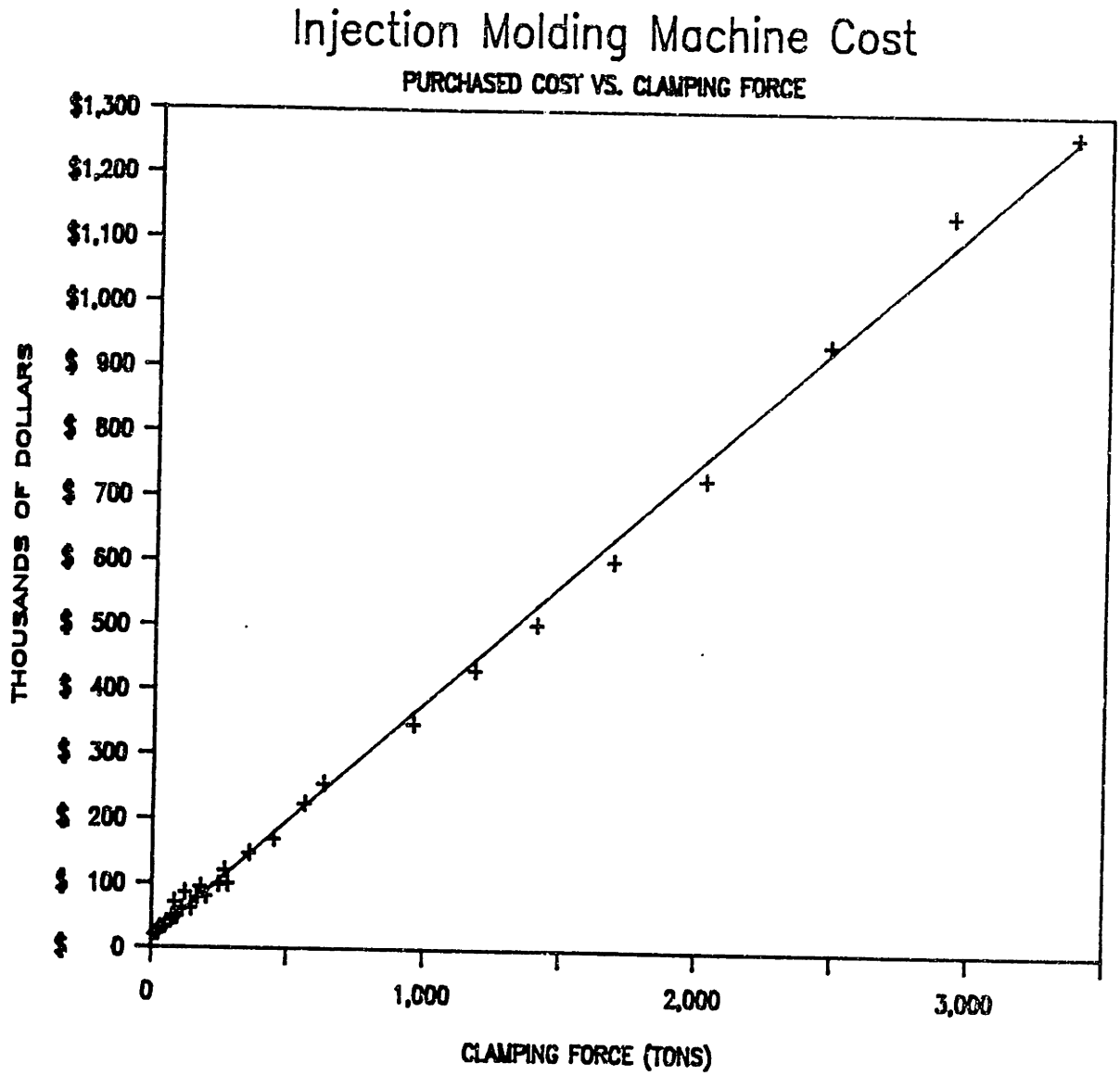

Figure 10. Injection Molding Machine Cost: Battenfeld Data, May 1986

by a material-dependent factor to capture the effect (if any) of the material being molded upon the lifetime of the equipment. Thus, the annualized cost of the main machine is calculated by the following equation:

$$\text{Annual Machine Cost} = \frac{\text{Machine Investment} * \text{Number of Streams}}{\text{Machine Life} * \text{XML(material)}}$$

The number of streams is estimated in "Number of Parallel Streams" on page 100. Its value and significance depends upon whether or not dedicated equipment is assumed. When the equipment is dedicated, the number of streams is an integer equal to the number of machines required to complete the production run. The total capital investment for these machines is divided by the estimated machine life to yield the annualized machine cost.

On the other hand, if it is assumed that the equipment is non-dedicated, the number of streams will have a "real number" or floating point value. In this situation, only that fraction of the total investment proportional to the time requirement for the production run is distributed onto the equipment life. The costs of molding the specified components recover only a fraction of the total investment. Effectively, these components incur machine costs only for the time in which the equipment is in use, as if the equipment is rented.

For the case study, the model estimates that the run-time for one machine is 125%, so that two machines and two sets of tools are required. Since dedicated equipment is assumed, the full cost of both machines is recovered. The model estimates that these machines must have 258 tons of

clamping force, and cost $110,000 each. The cost of the machines contributes $0.08 or 5.7% to the total piece cost.

TOOLING COST

Analogous to the main machine cost, the first step in accounting the cost of tooling is to estimate the total investment for one set of tools. Again, a statistically established cost equation is employed. However, the tooling equation is considerably less accurate than the machine equation, as there are a wide variety of factors that effect the cost of tooling, including the part design, the toolmaker, the material employed in the tool, and the precision or quality of the tool. Many of these factors are difficult or impossible to quantify.

The equation used to estimate the cost of a set of tools is:

$$\text{Tool Cost} = (0.220\ \text{Wgt}*\text{Cav} + 0.423\ \text{Area} + 538\ \text{Actns} + 339) * \$30.00/\text{hr}$$

0.220 (hr/g) - Weight Factor (See input parameters)
0.423 (hr/sq cm) - Area Factor
538 (hrs) - Action Factor
339 (hrs) - Constant
$30.00 ($/hr) - Toolmaker Shop Rate

Tool costs predicted by this equation are compared graphically with actual tool costs in Figure 11 on page 81.

The equation estimates tool cost as a function of total shot weight, projected area, whether or not there are "actions" built into the tool, and on an average fully loaded toolmaker shop rate. Ostensibly, the equation

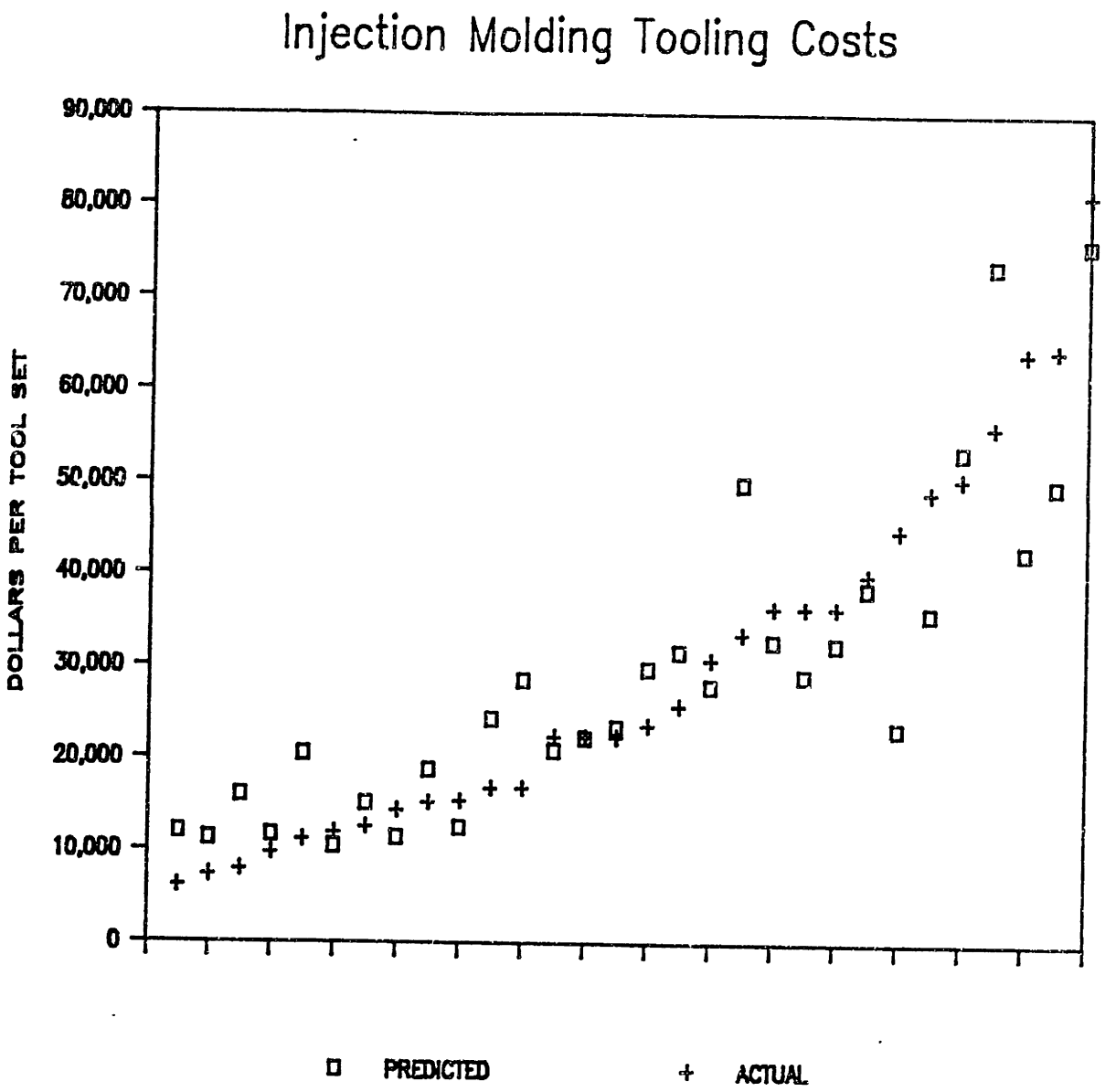

Figure 11. Injection Molding Tooling Costs

first estimates the number of machinist hours required to machine a set of tools, then multiplies this by the fully loaded shop rate for machine shop time. The coefficients within the parenthesis of the equation are dimensioned to yield estimates of the time requirement associated with part weight, surface area, etc.

In truth, the raw data for the above regression analysis were not based on labor hours. Rather, they consisted of the price of each tool set, as well as the weight, area, etc. of the component produced by that tool. These data were first converted into an equivalent number of machinist hours by dividing price by the estimated fully loaded shop rate. The statistical analysis was performed on these converted data. Details of this conversion and analysis are provided in Appendix B.

Price data were converted to equivalent machinist hours to make the tooling equation more applicable for different regions of the world. Fully loaded machine shop rates vary tremendously from region to region, and this variation directly effects the regional cost of tooling. On the other hand, it has been postulated that the amount of time required to machine a set of tools is less subject to regional variation (20). The tooling cost estimating equation is based on machinist hours, and a separate input is provided for defining the toolmaker shop rate. This last parameter must be adjusted according to the cost of machine shop time in the region of interest.

The annual cost of tooling is estimated by dividing the total investment cost by the productive lifetime of the tool, measured in years. The

total investment is the cost of one set of tools multiplied by the number of machines required to complete the production run. Estimation of the productive life of the tooling is described in "Productive Mold Life" on page 92.

Unlike the main machine estimate, there is no question of dedicated versus non-dedicated equipment with tooling; tools are always dedicated to the production of one component. Therefore, the equation for estimating the annualized cost of tooling is:

$$\text{Annual Tooling Cost} = \frac{\text{Tooling Investment} * \text{Number Machines}}{\text{Productive Tooling Life}}$$

Piece costs of tooling are estimated by dividing annual costs by the annual production volume.

Because of the inherent uncertainty in estimating tooling costs, an optional input variable for overriding the estimated value has been built into the model.

For the case study trash bin, the model estimates the investment cost of each tool set to be $43,356, resulting in $0.05 piece cost or 4.0% of the total cost. This estimate is based on the specified part weight and projected area, and assumes that only one cavity will be used and that the tool will not contain slides, cams, or other tool actions. For comparison, a part very similar to the trash bin was molded on a tool costing $39,000 (21).

OVERHEAD LABOR COST

Overhead labor cost is estimated as a fraction of other fixed costs. The fraction is specified by a process related input factor, and is 35% in the case study. Overhead labor is accounted as a percentage of fixed costs because it is assumed that overhead is independent of production volume. Of course, this is not entirely true. As production volumes increase, the overhead requirements will also generally increase.

Other cost estimating methods account for overhead labor as a percentage of direct labor costs with the use of variable burden (see "Material Cost Plus Loaded Shop Time" on page 13). In the injection molding model, burdens can be included by adjusting the wages of direct labor. However, traditional burden rates that range from about 100% to 400% should not be employed, as these burdens generally account for the cost of elements that are explicitly estimated by the technical cost method. Applying traditional burden rates to the direct wages within the model effectively double-counts many of the cost elements.

BUILDING COST

Building cost is computed on the basis of the amount of building space required to manufacture the specified component. The required building space is computed in "Required Building Space" on page 101, and is priced

by one of the exogenous cost factors. Specifically, the annualized cost of the building is estimated as:

$$\text{Building Cost} = \frac{\text{Required Building Space} * \text{Price Building Space}}{\text{Building Recovery Life}}$$

The total building cost is divided by the accounting lifetime of the building to yield an annual cost. This value is then divided by the total number of components being produced annually to yield piece cost. If the equipment is not dedicated, this value is also multiplied by the fraction of the year necessary to produce the specified number of parts.

For the case study, the model estimates that 176 square meters of space are required for the machines and for parts warehousing, costing $140,936 and contributing $0.02 to the piece cost.

INSTALLATION AND AUXILIARY EQUIPMENT COST

Installation cost is estimated as a fraction of the main machine cost. Auxiliary equipment cost is also estimated in this manner, except that the auxiliary equipment equation includes a material multiplier that captures the costs of the special equipment required for processing certain materials. Specifically, the equation for estimating auxiliary equipment costs is:

Auxiliary Equipment = 20% Main Machine Cost * XAU(Material)

20% - Auxiliary Equip. Cost (See input parameters).

The total investment cost in auxiliary equipment is divided by the machine lifetime and multiplied by the number of parallel processing streams to estimate annual cost. Implicitly, this equation presumes that auxiliary equipment is exactly as long-lived as the main injection molding machine. Also, this presumes that if the the main machine is dedicated to the production of one part, so are the auxiliaries.

The rigidity of these assumptions can be relaxed by changing the computational basis for this cost element. Specifically, it may be appropriate not to multiply the auxiliary equipment investment by the number of parallel streams, when one set of auxiliaries services many molding stations.

MAINTENANCE COST

Maintenance costs are computed as a fraction of the total cost of all equipment (main machine, tooling, auxiliary equipment, and building). This cost is then equally divided over the number of parts produced annually. When equipment is not dedicated, maintenance costs are multiplied by the fraction of the year that the equipment is needed for the specified production run.

COST OF CAPITAL

The annual cost of capital is computed based upon the assumption that the money used to purchase the various fixed capital investments is borrowed, and that it is paid back over the respective accounting lifetimes of each of these investments. The cost of capital for any one of the fixed assets (building, machine, tools) is computed by the standard engineering economics formula for capital recovery.

The capital recovery formula computes the amount of money, paid in equal installments over the life of the "loan", which will pay off a debt incurred at the present. For a loan based on N payment periods, at an interest rate of R% per period, to pay off an initial debt of I dollars, this formula is:

$$\text{Payment} = I * \frac{R * (1 + R)^N}{(1 + R)^N - 1}$$

In general, the fraction of this payment which is interest and the fraction which is for repayment of the loan principal varies according to the period in which the payment is made. In the injection molding model, a simplifying assumption has been made; the interest fraction is averaged over the life of the loan, and this average is taken to be the cost of capital. The "average" annual cost of capital is computed from the following equation:

$$\text{Cost of Capital} = I * \frac{R * (1 + R)^N}{(1 + R)^N - 1} - \frac{1}{N}$$

This formula is systematically applied to each of the capital investments. Each of these investments is recovered over their respective accounting lifetimes. The capital recovery rate (R) is constant for all investments, and is one of the exogenous cost factor inputs.

Added to the costs of these investments is the cost of working capital. Working capital is the amount of money tied up in inventories, payrolls, and other short-term expenses that is kept on-hand in order to conduct business. In this model, it is assumed that the "investment" in working capital is equal to a specified number of months of variable costs. The working capital period is three months in the case study, and this value is one of the exogenous cost factor inputs of the model. The interest charges for working capital are computed exactly as for the other capital investments.

The interest portion of all of the capital loan payments are summed to yield the total cost of capital for the component. If the equipment is not dedicated, this sum (except for the tooling costs) is multiplied by the fraction of the year that the equipment is required to produce the required number of parts.

In the case study, which was based on the assumption of dedicated equipment, the total cost of capital was estimated to be $0.10 per piece or $38,880 per year. Although not shown in Figure 9 on page 72, this annual cost can be broken down by contributing element as follows:

Machine, Auxiliary, & Installation	$16,343
Tooling	$4,394
Building	$8,731
Working Capital	$9,412
Total	$38,880

ADDITIONAL INFORMATION

As indicated above, many of the cost elements are based upon other estimated values. These values are computed and displayed in the additional information section of the model, and for the case study, appear at the bottom of Figure 9 on page 72. The equations for estimating each parameter are presented in the following sections.

RAW MATERIAL PRICE

The raw material price, retrieved from the materials database, is output for review by the model's user. No new computations or adjustments are involved in generating this figure.

SCRAP RATE

The scrap rate is computed by multiplying the base scrap rate parameter, as input in the process related factors section, by the material multiplier (XSC) and the geometry multiplier (YSC), to account for variations in scrap

rate attributable to the material and geometry, respectively. The result of this computation is displayed and is used in the equation that estimates material cost. For the case study, the scrap rate was estimated to be 2.0%.

Scrap rate should not be confused with rejection rate of finished parts, which is not considered in the current version of the injection molding cost model. Scrap rate, as employed, only accounts for the cost of nonrecoverable raw material. Rejection rates usually apply to finished parts that are must be thrown away due to defects in workmanship.

ESTIMATED TOTAL EXTERNAL SURFACE AREA

The total external surface area of the part is equal to the area of a uniform sheet of material having the same weight and nominal wall thickness as the molded part, and made from the same material. In other words, it is the projected area of the part when flattened into a uniform sheet. External surface area is computed by the following equation.

$$\text{Ext.Area} = \frac{\text{Weight}}{\text{Density(material)} * \text{Nominal Wall Thickness}}$$

The material density is retrieved from the materials database, and the weight and nominal wall thickness of the part are specifed as input parameters. The external surface area of the part does not directly effect any of the cost elements in the injection molding cost model. It is used to

compute the next additional information parameter, "mold complexity factor".

MOLD COMPLEXITY FACTOR

The mold complexity factor is the ratio of the total external surface area to the projected area. This ratio is indicative of the degree of curvature, convolution, and/or gereral complexity of the molded part. The mold complexity of a flat piece is 1.0 - the lower limit or the least "complex". Hemispherical parts have "complexity" equal to 2.0, the ratio of the area of a hemisphere to that of a circle having the same radius. The trash bin, which is tall in comparison with its width and depth, has a complexity ratio of 6.26. The most "complex" component surveyed in all case studies had a complexity factor of 6.56.

The mold complexity factor is not used in any of the cost or additional information equations in the injection molding model. It was hypothesized that this factor would be a significant explanatory variable for estimating tooling costs and cycle times. However, for the case studies examined, both of these hypotheses were incorrect. In other process models (e.g., SMC), the mold complexity factor has been successfully used to explain some of the cost of tooling.

ENERGY ADJUSTMENT FACTOR

The energy adjustment factor is used to account for the differences in energy consumption that arise from the choice of material. This factor is computed as the ratio of the heat required to melt the material to the heat required to melt general purpose polystyrene.

$$\text{Energy Adj. Factor} = \frac{\rho \; Cp \; (T.melt - T.room)}{\rho^{*} \; Cp^{*} \; (T.melt^{*} - T.room^{*})}$$

* - baseline, referenced to general purpose polystyrene
ρ - density
Cp - heat capacity
T.melt - process melt temperature
T.room - room temperature (20C)

The premise underlying this equation is that differences in energy consumption can be accounted for by comparing the energy required to melt the baseline and molded materials. The energy adjustment factor from the case study is 1.64, indicating that 64% more energy is required to process Stamylan® LDPE than general purpose polystyrene. This equation does not account for differences in the energy required for drying or transporting alternative materials.

PRODUCTIVE MOLD LIFE

The productive life of the tooling is the lesser of two numbers. The first number is the input value for the product life, the number of years during

which the same molded part is produced. The second number is the physical life of the tool, and is estimated according to the following equation:

$$\text{Physical Life} = \frac{\text{Baseline Mold Life} * \text{XML(matl)} * \text{YML(geo)}}{\text{(Annual Volume / Parallel Streams / Cavities)}}$$

The physical mold life is calculated by multiplying the baseline mold life by the material mold life factor (XML) and the geometry mold life factor (YML), yielding the maximum number of times that a tool can be cycled before wearing out. This quantity is divided by the number of times each mold is cycled in a production year, which is calculated by dividing the annual production volume by the number of parallel streams and by the number of cavities in the tool. For this equation, the number of parallel streams must be taken as an integer value, since it is not meaningful to consider non-dedicated tooling. The result of this calculation is the maximum number of years that the tool can remain in service.

The physical tool life is compared with the product life and the lesser of these becomes the productive mold life, and is used as the basis for recovering the investment in tooling. In the case study, the product life (4 years) is the limiting value. The physical tool life for the case study is 5 years (1,000,000 cycles/400,000 per year/2 parallel streams).

CLAMPING FORCE

The clamping force of the injection press is either specified as an optional input to the model, or is estimated by the following equation:

$$\text{Clamp Force} = \text{P.Area} * \text{Cavities} * \left(\frac{224 \text{ bar rt.cm}}{\sqrt{\text{Nominal Wall}}} + 172 \text{ bar}\right)$$

P.Area - projected area
Cavities - number of cavities in the tool
Nominal Wall - average wall thickness
172 bars - Mold Pressure Intercept (See Figure 4 on page 53)
224 bar rt.cm - Mold Pressure Slope

Clamping force is often specified independent of the projected area and wall thickness of the component. This occurs because molding businesses typically have a limited number of machines, and production scheduling prescribes which machine is used. Therefore, the option to specify clamping force exogenously has been incorporated into the model.

If clamp force is not specified, it is estimated from the product of the total projected area in the mold and the averaged maximum pressure of the melt during injection. Total projected area is equal to the projected area of the component multiplied by the number of cavities in the tool. The relationship for estimating mold pressure as a function of nominal wall thickness appears graphically in Figure 4 on page 53. This product of the projected area and pressure is the force normal to the platens of the press.

Clamping force is used to estimate the investment cost of the molding machine, according to the main machine equation presented above and the relationship displayed in Figure 10 on page 78. In the case study, the model estimates that 258-ton machines costing $110,000 each are required. A component very similar to the case study trash bin is molded on a 250-ton machine (22).

COOLING TIME

The time for the melt to cool to ejection temperature is estimated from theoretical considerations according to the following equation (23):

$$\text{Cool Time} = \frac{d^2 \rho \, Cp}{\Pi^2 k} * LN \left(\frac{8 \; (T.melt - T.mold)}{\Pi^2 \; (T.eject - T.mold)} \right)$$

d - nominal wall thickness (cm)
ρ - density (g/cc)
Cp - specific heat (J/g/K)
k - thermal conductivity (W/cm/K)
T.melt - process melt temperature
T.mold - temperature of the tool surface
T.eject - bulk temperature of the part at ejection

The cooling time equation is derived from transport theory for the mean temperature distribution in a slab of finite thickness undergoing cooling (24). Because this equation is based on a slab geometry, it does not reliably estimate the cooling time for other shapes, including spherical and cylindrical components. Fortunately, most injection moldings are "slab-like", in that they have relatively thin and uniform wall thickness.

In the model, the equation uses the specified nominal wall thickness of the component and data retrieved from the materials database to calculate the theoretical cooling time.

The estimated cooling time is generally much shorter than the total cycle time. For instance, in the case study, the time for cooling is 8.8 seconds out of a total of 36.8 seconds. In addition to cooling, the mold must open, the part must eject, the mold must close, and molten plastic must be injected. Each of these events in the molding cycle contributes to the total cycle time.

TOTAL CYCLE TIME

The total cycle time is established one of two ways. If the user has supplied an "optional" value for cycle time in the input area, this value is used. Otherwise, total cycle time is estimated from the sum of the cooling time and the time for other events in the molding cycle.

The equation for estimating cycle time is founded on theoretical considerations, but is established through statistical analysis of case studies. The theoretical considerations underlying the equation are that, 1) cycle time relates to the time to cool from the melt, and 2) cycle time relates to the size of the part being molded. The second consideration can be phrased, "bigger parts take longer to mold". These two considerations yield the funcional form of the equation; the coeficients for the terms in this equation are established statistically (see Appendix B).

$$\text{Cycle Time} = 1.35\ \text{Cool Time} + 0.0151\ \text{Weight} * \text{Cavities} + 8.87$$

The coefficient on the cooling term is 1.35, 35% greater than unity -- the expected value. This discrepency could arise from a number of sources, including the fact that neither the temperatures nor the physical properties that are used to estimate the cooling time remain constant through the cooling cycle. If, for instance, the temperature of the mold surface increases significantly during the cooling cycle (which is to be expected), the cooling time equation will consistently underestimate the actual cooling time.

The product of part weight and cavities is an estimate of the total shot weight (neglecting runners, sprues, flash, etc.). The coefficient on this term (0.0151) has the dimensions of seconds per gram. For the collected case studies, shot weight is the parameter that yields the best statistical correlation with cycle time, and therefore, best captures the effect of part size. Projected area was evaluated as an alternative proxy for size, but did not yield comparable statistical correlations.

The constant term suggests that irrespective of the cooling time and part size, a minimum cycle time of 8.87 seconds is required. This lower limit cannot be explained from strict theoretical considerations. The constant term, like the weight term, reflect current injection molding technology, and may be expected to change in the future. These values also reflect the case studies from which they were derived, and might change significantly if derived from a different data set.

In the trash bin case study, the total estimated cycle time is 36.8 seconds, of which 1.35 times 8.8 seconds, or 11.88 seconds, are associated with cooling the melt. Cooling represents 32% of this total cycle time. For the other case studies, the calculated cooling time ranged from 10% to 92% of the total cycle time, with an average contribution of 35%.

COST OF SHOP TIME

The cost of shop time is established from one of two bases; either by direct specification or by estimation. If the user directly specifies this parameter, all of the cost elements except material, main machine, and tooling become "not applicable", and the cost estimation is performed on the basis of material plus loaded shop time (see "Material Cost Plus Loaded Shop Time" on page 13). Under this condition, cost is computed as:

$$\text{Total Cost} = \text{Material Cost} + \text{Cost of Shop} * \text{Cycle Time} + \text{Tool Cost}$$

If the cost of shop time is not specified, the elements of cost are estimated by the technical cost method, and the cost of shop time is computed from the total fabrication cost (except material and tooling costs) divided by the cycle time and the number of cavities. The equation for estimating the cost of shop time is:

$$\text{Shop Cost} = \frac{\text{Total Cost per Piece} - \text{Material Cost} - \text{Tooling Cost}}{\text{Cycle Time} * \text{Number of Cavities in Tool}}$$

The result of this equation is an estimate of the fully loaded cost, in dollars per hour, for running the molding machine. This result is presented strictly for information purposes; it is not used for cost estimation within the model.

In the case study, the cost of shop time is not directly specified, and is estimated to be $52.49 per hour.

RUN-TIME FOR ONE MACHINE

The run-time for one machine is the percentage of the work year that one machine must run in order to produce the annual production volume. This parameter is computed from the following equation:

$$\text{R.Time} = \frac{\text{Cycle Time} * \text{Annual Production Volume}}{\text{Hrs/Day} * \text{Days/Yr} * \text{Cavities} * \text{Productivity}}$$

16 Working Hours/Day (See input parameters)
240 Working Days/Year
Number of Cavities
85% Productive Time (% total time)

For the trash bin case study, the run-time for one machine is 125%, indicating that a single machine cannot produce the annual production volume, given the estimated cycle time and specified working hours per day, working days per year, etc.

The estimated run-time for one machine should be reviewed each time a cost estimate is performed. If its value is close to, but slightly less than, an integer value, the assumption of dedicated equipment may be most

appropriate. If run-time for one machine is slightly larger than the closest integer value, non-dedicated equipment is often the best accounting assumption, unless a large number of parallel streams are required. Changing the specified number of working hours per day or days per year will effect the run-time for one machine, and may be used to realize full utilization of all equipment.

By iteratively adjusting the input parameters that effect the run-time equation, it is possible to help define the least-cost manufacturing conditions. For instance, it is possible to assess whether adding a third work shift is more cost effective than buying another machine, set of tools, etc.

NUMBER OF PARALLEL STREAMS

The number of parallel streams is estimated by one of two possible methods. If non-dedicated equipment is assumed, it is equal to the run-time for one machine. If dedicated equipment is assumed, the number of parallel streams is equal to the next integer greater than the run-time for one machine.

Each of the fixed cost investments is multiplied by the number of parallel streams in estimating the per year and per piece cost bases. In the case study, the machine investment ($110,000) is multiplied by the number of parallel streams (2.00) and divided by the machine life (7.2 years) to yield the annual machine cost ($30,555/yr). If the case study had been

conducted assuming non-dedicated equipment, the number of parallel streams would be 1.25, and the machine cost would be proportionately reduced.

Everything else equal, dedicated equipment always results in higher production costs than non-dedicated equipment. In practice, the productivity, number of laborers per machine, scrap rate, and other parameters are effected by whether or not the equipment is dedicated. To generate meaningful comparisons between the costs of dedicated and non-dedicated equipment, these parameters should be adjusted appropriately.

REQUIRED BUILDING SPACE

Required building space is calculated from a log-linear regression that relates space requirements to the size of the part being produced. Again, part weight is used as the best indicator of part size. The building space required for one machine is computed by the following equation:

$$\text{Space} = 135 * (\text{Weight} * \text{Cavities})^{0.71} * (1 + (0.3\ \text{Nmch} - 1))$$

135 square meters - Floor Space Coefficient (See input parameters)
0.71 - Floor Space Scaling Exponent
Nmch - number of parallel streams

The estimated building space includes area required for the molding machine, auxiliary equipment, material storage, and parts warehousing. The space requirement for a single machine operation is estimated, then this number is increased by 30% for each additional parallel operation to yield the total required building space. Additional processing streams do not

occupy as much space as the first stream because of shared material storage, parts warehousing, etc.

Most molding businesses own several molding machines, all housed in a single building. These machines are used to produce many different components and there may be no demarcation of space by production run. Therefore, the building space requirement as estimated by the above equation is difficult or impossible to validate precisely.

CURRENCY CONVERSION FACTOR

The currency conversion factor is retrieved from the currency conversion menu in the input parameters, and is output for review by the model's user. No new computations or adjustments are involved in generating this figure. It is multiplied by the cost elements and the cost related additional information to convert their values to a foreign currency basis.

SUMMARY OF THE INJECTION MOLDING COST MODEL

The injection molding process is modeled as a stand-alone process for converting plastic raw materials into molded shapes. The costs of this process are divided into two categories, variable costs and fixed costs. Each of these categories is further subdivided into cost elements, and each element is estimated separately.

The equations for estimating the cost elements are provided in the preceding sections. These equations are based on theoretical considerations, engineering judgments, and statistically derived relationships. The injection molding model is nothing more than a synthesis of these equations into a single computerized framework.

This description of the injection molding model may foster the impression that an untrained person can use the model to estimate costs in one pass. In practice, the model should be applied iteratively, and by experienced cost estimators. The first estimate produced by the model is rarely the best one. An experienced cost estimator will systematically incorporate his experience and intuition into the model, and into the estimate. The model thus becomes a tool for thinking about the process and a means of gaining insight into process economics.

Technical cost models demonstrate the advantages of combining engineering know-how with a disciplined economic assessment of a manufacturing process. Even though the injection molding model embodies a number of simplifying engineering assumptions, the level of technical detail in the model far exceeds that of other more common cost estimating techniques. By improving the engineering analysis, one may improve the cost estimate further, but there are limits to the value of such modifications.

A final feature of cost analysis that has not been directly addressed is the dynamic nature of costs. Costs not only change from day to day, they also change from region to region. The fact that the data set of a technical cost model can be easily updated or revised to reflect these spa-

cial and temporal changes is another advantage to this approach. However, it also represents a duty which must be attended to regularly, if the quality of the cost estimates generated by a model is to remain high.

While being able to estimate piece costs on the basis of a set of manufacturing and engineering assumptions is an attractive consequence of constructing this sort of model, it is the framework for the calculation that provides the greatest benefit. By enforcing a discipline upon the cost estimating process, a consistent and easily justifiable cost estimate can be computed rapidly. Furthermore, the consequences of alternative processing and engineering assumptions can be evaluated on a consistent basis, as will be demonstrated in the next section.

INJECTION MOLDING SENSITIVITY ANALYSIS

Sensitivity analysis is the technique of systematically varying one or more input parameters and examining the effect that these variations have on the output. In technical cost analysis, this might typically involve varying the cycle time, annual production volume, or material price, and examining their influence on total part cost.

The importance of a sensitivity analysis lies in the fact that uncertainty surrounds all variables in a cost estimate. The estimated cycle time, for instance, may differ from the actual production value by more than one hundred percent. Even the material price may not be known accurately in advance. Given uncertainty, sensitivity analysis can be used to

quantify the effect that a change in one variable has on the primary output, in this case total cost. By knowing the extent to which changes in input parameters change total cost, it is possible to identify the most important uncertainties, and focus attention on ascertaining their actual values.

Two sensitivity analyses were performed on the injection molded trash bin estimate of the previous section. These are: 1) sensitivity to changes in cycle time, and 2) sensitivity to changes in annual production volume. Each of these analyses were conducted on the basis of two different assumptions, dedicated equipment and non-dedicated equipment. The results of these analyses are presented graphically in Figure 12 on page 106 and Figure 13 on page 110 respectively, and are discussed below.

SENSITIVITY OF COST TO CYCLE TIME

The sensitivity of variable, fixed, and total costs of production to changes in the cycle time are presented in Figure 12 on page 106. This analysis was performed by varying the cycle time from 20 seconds to 60 seconds in two second increments while tabulating changes in the costs. Over this range of cycle times, and depending on whether the equipment is dedicated or not, the total cost ranges from about $1.10/piece to about $1.60/piece.

In this sensitivity analysis, there are two fixed and two total cost curves. These curves are for the cases of dedicated and non-dedicated

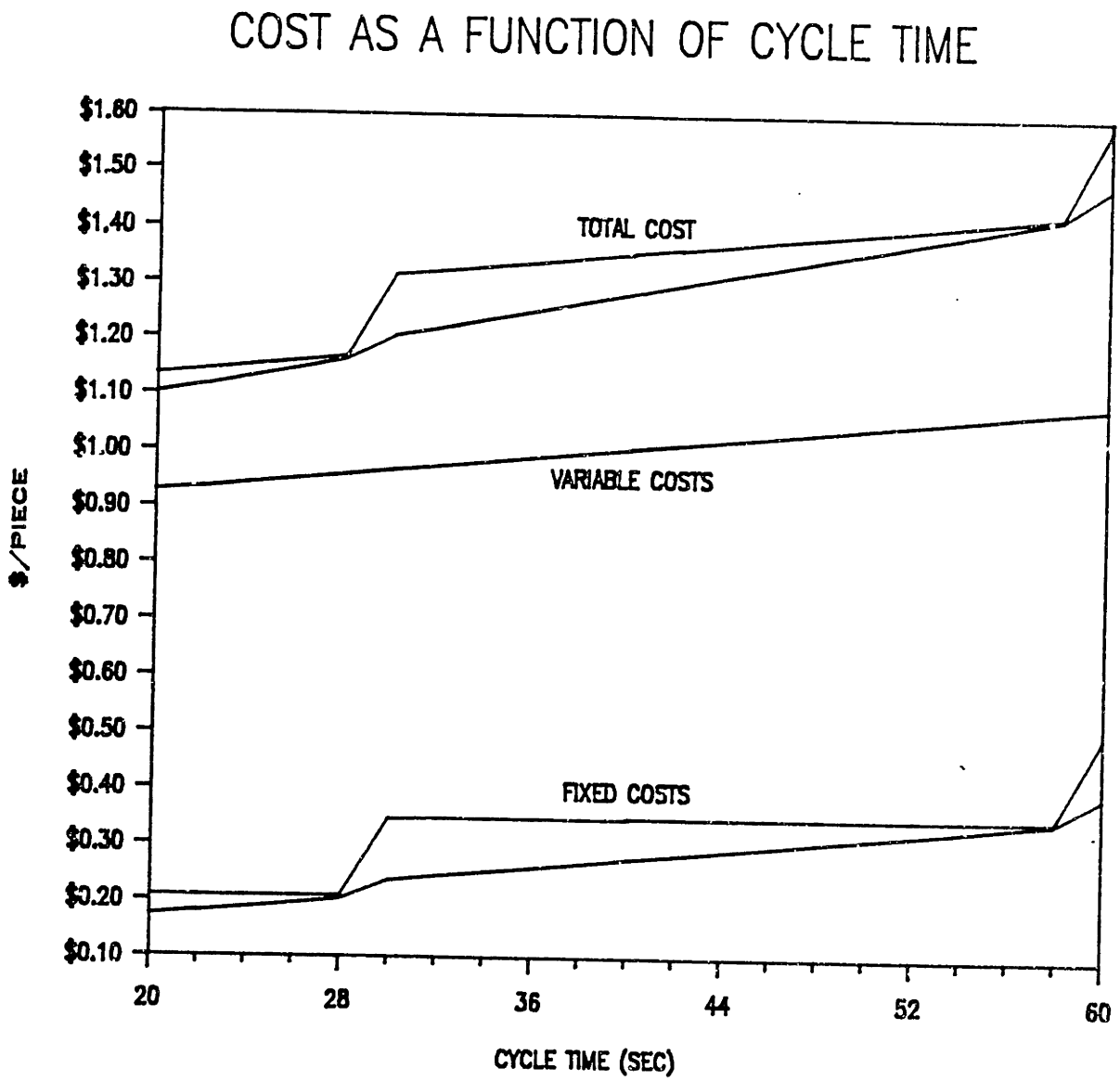

Figure 12. Sensitivity of Cost to Cycle Time: Case Study - Rubbermaid Model 2845 Trash Bin

equipment, respectively. The dedicated equipment curves are the ones with larger cost values, because everything else being equal, it is always more costly to buy equipment expressly for making one component, leaving it idle when the production run is complete.

Of the variable cost elements, only direct labor is effected by changes in the cycle time; material and energy costs are not. Cycle time directly influences labor cost, by establishing the labor content in each part. As cycle time increases, the quantity and cost of labor to make the component also increases.

The slope of the variable costs curve is equal to the effective direct labor wage, including the effect of lost productivity. In the sensitivity analysis, the value of this slope is $13.68/hr. The intercept of the variable costs curve (at zero cycle time; not shown) is the sum of the material and energy cost elements.

Variable costs are not effected by a change in the equipment accounting basis from dedicated to non-dedicated. Therefore, only one variable cost curve appears.

The shapes of the fixed cost curves are quite different from that of variable cost curve, and they are different from each other. Both fixed cost curves show a step change in value at the point where cycle time is equal to 28 seconds, and again when cycle time equals 58 seconds. In the dedicated equipment curve, this step change is much larger. The step in value results from the additional process stream that is required when the

cycle time exceeds these limits. Adding a parallel stream involves capital expenditures in equipment, tooling, building, etc.

The positions of the break-points where additional streams are required are predicated on a number of input assumptions, including the annual production volume (400,000), the number of working days per year (240), the number of hours worked per day (16), and the labor productivity (85%). A change in any of these parameters will effect the position of the break-points along the cycle time axis.

The fixed cost curve for dedicated equipment remains flat until the second process stream is required. At this point, fixed costs jump to a higher level, then remain constant until a third stream is needed. This step-wise behavior is characteristic of the use of dedicated equipment. Dedicated equipment fixed costs depend only on the capital investment and the number of parts produced. The step changes shown in Figure 12 on page 106 result when a larger investment is required to produce the same number of parts.

On the other hand, the fixed costs for non-dedicated equipment rise continuously with increasing cycle time. This behavior is a result of the fact that with increasing cycle time, a larger fraction of the capital investment is distributed onto the parts produced.

The small, but observable, step-wise jump in the non-dedicated cost curve at the break-points results from the contribution of tooling costs. Tools, by their nature, are always dedicated equipment. Once the cycle time reaches a break-point, an additional set of tools is required, and a

jump in fixed costs results. This jump is much smaller than the associated jump in the dedicated equipment curve because the investment in tooling (for the trash bin) is much less than the investment in machinery.

At the point where cycle time equals 28 seconds in the sensitivity plot, the fixed costs are equal for both the dedicated and non-dedicated assumptions. This occurs because, at this point, one machine must run continuously throughout the year in order to produce the annual production volume. Under these conditions, there is no difference between the assumptions of dedicated and non-dedicated equipment.

SENSITIVITY OF COST TO ANNUAL PRODUCTION VOLUME

The sensitivity of production costs to changes in the annual production volume are presented graphically in Figure 13 on page 110. This analysis is conducted over a range of from 100,000 to 700,000 parts per year. Over this range, unit costs vary from $1.72 to $1.24 per piece.

Variable costs, by definition, are independent of annual production volume. This feature is clearly demonstrated in the sensitivity plot.

Again, the total and fixed cost curves are presented for the cases of both dedicated and non-dedicated equipment. At any production volume, the fixed costs for dedicated equipment are larger than the corresponding non-dedicated equipment value.

The discontinuities in the cost curves at 300,000 and 625,000 units per year are the result of adding additional process streams. One machine

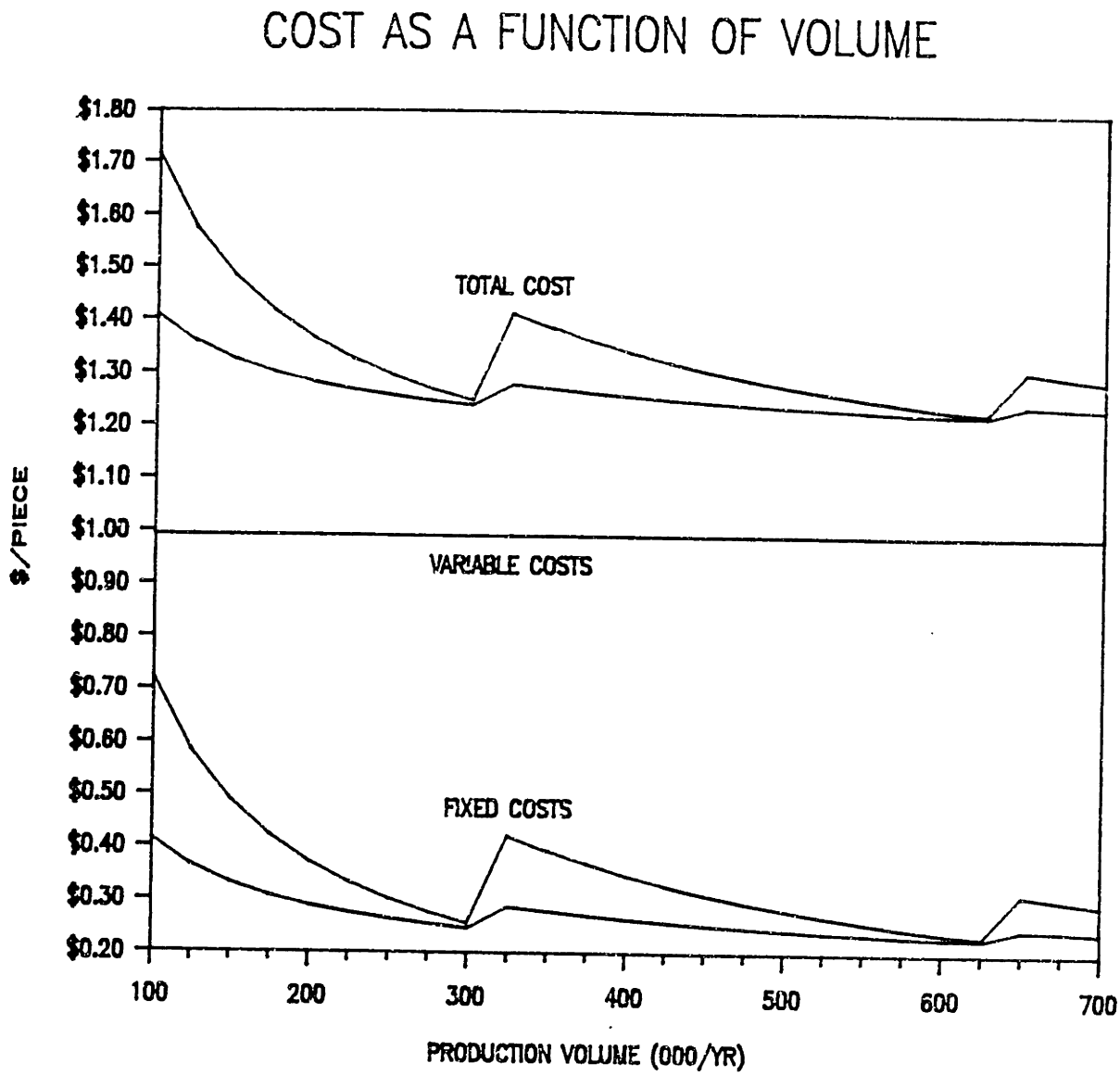

Figure 13. Sensitivity of Cost to Production Volume: Case Study - Rubbermaid Model 2845 Trash Bin

working 16 hours per day, 240 days per year, with a 36.8 second cycle time, and with 85% effective productivity, cannot produce more than 300,000 pieces. As discussed in the preceding section, this step change is greater when assuming dedicated equipment. The small step in the non-dedicated curve is due to tooling, which is always dedicated.

SUMMARY OF SENSITIVITY ANALYSIS

In summarizing sensitivity analysis, it must be pointed out that the results of the two preceding analyses apply only to the trash bin, and cannot be construed to injection molding in general. Sensitivity analysis is presented to demonstrate the technique, not to provide general conclusions about injection molding.

For the trash bin, sensitivity analysis revealed that a change in either the cycle time or the annual production volume can result in a significant change in the total cost. Given a technical assessment of the minimum and maximum expected cycle times, or a business assessment of minimum and maximum production volumes, the cost implications of these uncertainties can be easily quantified.

The cycle time analysis indicates that total cost is more sensitive to changes in cycle time if non-dedicated equipment is assumed. This effect occurs because longer cycle times result in a larger fraction of the capital investment being distributed onto the same number of pieces.

Conversely, total cost is more sensitive to changes in production volume when dedicated equipment is assumed, because under this assumption, the entire capital investment is distributed onto the parts produced. With more parts produced, the cost per part is reduced.

In both sensitivity analyses, it was shown that the costs of non-dedicated equipment represent a limit or asymptote that can only be approached by dedicated equipment. Since many molding businesses operate somewhere between having dedicated and non-dedicated equipment, these two assumptions might also serve to bracket the expected cost of injection molding trash bins.

The value of sensitivity analysis is that it is a method for dealing with the uncertainty inherent in cost estimation. Sensitivity analysis provides a basis for bracketing the cost estimate, taking into account a range of possible values for the inputs or assumptions. In many instances, this information is more valuable than the single point cost estimate obtained from cost analysis.

SHEET MOLDING COMPOUND COST MODEL

The sheet molding compound (SMC) model estimates the costs of the two main processing steps associated with SMC. These two steps are: 1) making the SMC sheet, and 2) molding the SMC sheet into a component. The SMC model is inherently different from the injection molding in this respect. Injection molding is modeled as a stand-alone process; SMC is modeled as two coupled processes. The nature and ramifications of this difference are described in a later section.

The model is organized on a spreadsheet as shown in Figure 14 on page 114. This section of the thesis is organized in a manner similar to the structure of the model. A separate subsection is provided for each of the major column headings. Within each subsection the inputs, formulae, and assumptions relevant to that column heading are briefly explained. Many of these factors are directly analagous to aspects of the injection molding model, and therefore, are not discussed in great detail.

FORMULATIONS

The "Formulations" section is used to select the type of SMC formulation, and to specify the composition of that formulation. The contents of the "Formulations" section are shown in Figure 15 on page 115. Formulation constituents are divided into four categories: resins, reinforcements, fillers and additives. Users may select from one of five prespecified for-

FORMULATIONS	SHEET LINE	SHEET MOLDING INPUTS	MOLDING COST ESTIMATE
Resins	Production rate	Component specs	Variable Cost
Reinforcements	Materials	Other Input	Fixed Cost
Fillers	Energy	Exogenous	
Additives	Labor	Process factors	Total
	Capital		
PROPERTIES & ADJ. FACTORS	TOTALS		ADDITIONAL INFORMATION

Figure 14. SMC Cost Model Structure

mulations, or may specify their own. The selected formulation is carried through the entire analysis.

The five prespecifed formulations within the model are:

1. (GP) - General Purpose: generic SMC for non-structural, non-class A applications. (Also, the baseline material for all "materials adjustment factors").
2. (LP1) - Low Profile: formulation for components requiring class A quality surface finish, but not involving ribs or thick sections.
3. (LP2) - Low Profile: for class A body panels containing ribs.

	Price ($/lb)	GP	LP1	LP2	HS	Other
POLYESTER RESINS		(Weight Percent)				
Generic Polyester	$0.55	33.0%				
DOW Derakane	$1.20					30.0%
ICI Atlac	$1.30					
USS 13110	$1.08					
Freeman Interpol	$1.42				30.36%	
Stypol 40-3941	$0.80			15.4%		
Stypol 40-3950	$0.95		25.2%			
Styrene Monomer	$0.30			1.3%		
REINFORCEMENTS						
E-glass	$0.75	32.0%	28.0%	28.0%	44.0%	60.0%
S-glass	$4.20					
Fiberglass roving	$0.54					
DuPont Kevlar	$16.00					
Carbon-high strength	$21.00					
FILLERS						
Antimony trioxide	$1.50					
Barytes	$0.06					
CaCO3-2.5 micron	$0.04					10.0%
CaCO3-5 micron	$0.03		45.3%			
CaCO3-7.5 micron	$0.02			44.8%	24.6%	
CaCO3-14 micron	$0.01					
Geo. kaolin-1 micron	$0.06	33.0%				
Geo. kaolin-5 micron	$0.06					
Diatomaceous earth	$0.07					
Talc	$0.02					
Feldspar-14 micron	$0.02					
Feldspar-9 micron	$0.03					
PQ Q-CEL Microspheres	$1.30					
3M Glass bubbles	$1.50					
Thickener MgO	$0.55	1.0%	0.3%			
Calcium Oxide	$0.04			0.2%		
ADDITIVES						
T-Butyl Perbenzoate	$2.05		0.4%	0.3%	0.2%	
Luperox 118	$8.05					
U.C. Neulon A (profiler)	$1.29			9.0%		
U.C. Neulon T (profiler)	$1.11					
Zinc Stearate	$0.77	1.0%	0.9%	0.9%	0.8%	
Zelec UN	$0.88					
PROPERTIES AND ADJUSTMENT FACTORS						
Cycle Time		1.00	1.50	1.50	0.90	1.00
Mold Life		1.00	1.00	1.00	0.80	1.00
Specific Gravity		1.86	1.94	2.09	1.79	2.03

Figure 15. SMC Formulations Data

4. (HS) - High Strength: for structural applications.

5. (Other) - user specified formulation.

PROPERTIES AND ADJUSTMENT FACTORS

The "Properties and Adjustment Factors" reflect the effect that the selection of a formulation has on various processing parameters. The property and/or factor and its effect are described below.

1. Specific Gravity: the specific gravity of the formulation is used to convert volumetric output (cu ft/min) to mass output (lbs/hr).
2. Mold Life Adjustment Factor: a multiplier that adjusts the mold life as a function of the formulation. This parameter is less than 1.0 for formulations which reduce mold life relative to the baseline general purpose (GP) formulation (for example, the mold life factor for high strength SMC, which is more abrasive than general purpose SMC, is 0.80).
3. Cycle Time Adjustment Factor: a multiplier that adjusts the molding cycle time as a function of the formulation. This parameter is less than 1.0 for formulations which cycle more rapidly than the baseline general purpose (GP) formulation (e.g., the high-strength formulation, which is used in applications where surface finish is not important, has a cycle time adjustment factor of 0.90).

SHEET LINE

The "Sheet Line" portion of the SMC model is shown in Figure 16 on page 118. This section of the spreadsheet is used to estimate the cost of producing the SMC sheet itself. It is modeled after the Navistar (25) sheet making line in Columbus, Ohio. Cost estimates made in this portion of the model are based on a particular configuration and scale of operations for manufacturing SMC sheet.

The limitation that this "snap-shot" aspect places on use of the model is that while the user may specify changes in line size or production rate, these changes will not effect the capital, energy, and labor costs for the sheet line. In the injection molding model, changes to the size of the machine or to the production rate do effect these cost elements.

The sheet line is not considered to be dedicated to the production of any given component. Rather, the sheet line runs at the specified production rate for the specified number of hours per day for the specified number of days per year.

The bottom line of the "Sheet Line" section is the cost ($/lb) of the sheet. Sheet cost is the variable by which the sheet line is coupled with the molding operation, as discussed in an upcoming section. This value can be overridden in the "Molding Cost Inputs" section if desired.

PRODUCTIVITY WHEN RUNNING	UNITS	
Linear Output	ft/min	26
Width	in	48
Thickness	in	0.1
Specific Gravity		1.94
Area Density	oz/sqft	16.14
OUTPUT =====>	lbs/hr	6295

EFFECTIVE PRODUCTIVITY	UNITS	
Working Days/Year	d/yr	240
Shifts/Day	shft/d	1
Hours/Shift	h/shft	8
Scheduled Downtime/Shift	hrs	2.2
Unscheduled Downtime/Shift	hrs	0.01
Unproductive Time/Shift	hrs	0
Effective Productivity		72.4%
Total Production Hours	hr/yr	1920
OUTPUT =====>	lbs/hr	4556

MATERIAL	UNITS	
Paste Scrap Rate	%	0.13%
Price of Paste/lb Sheet	$/lb	$0.27
Price of Reinforcement/lb Sheet	$/lb	$0.21
Sheet Scrap Rate	%	0.14%
TOTAL =====>	$/cwt	$48.13

ENERGY	UNITS	Rated	Dlvd	Effec
Mixers	hp	30.0	50.0%	15.0
Pumps	hp	10.0	70.0%	7.0
Calendering Rolls	hp	45.0	50.0%	22.5
Lighting & Controls	kW	5.0	100.0%	5.0
Total Electric Eqivalent	kW	38		
Price of Electricity	$/kWh	$0.080		
TOTAL =====>	$/cwt	0.067		

LABOR		
Fixed Number of Laborers		2
Variable Number of Laborers		2
Direct Labor Wages (w/ burden)	$/hr	$13.00
TOTAL =====>	$/cwt	$0.98

CAPITAL EQUIPMENT		$/unit ($000)	#	Total ($000)
Bulk Resin Storage Tanks		$28	4	$110
Bulk Storage Silo (6000 cuft)		$50	1	$50
Weigh Hoppers		$60	2	$120
Mixing Modules		$75	2	$150
Holding Tanks		$22	2	$44
Programable Controllers		$15	1	$15
Inline Paste Mixers		$15	2	$30
Glass Roving Feed & Chopper		$30	1	$30
SMC Machine		$350	1	$350
Auxiliary Equipment	5.0%			$32
Installation	33.0%			$213
TOTAL INVESTMENT	($000)	==========>		$1,144

CAPITAL RECOVERY		
Capital Recovery Period	yrs	5
Capital Recovery Rate		12%
Annual Production	lbs/yr	8.7E+06
TOTAL =====>	$/cwt	$3.63

SUMMARY OF COSTS - SHEET FORMING	$/cwt	percent
Materials	$48.13	90.24%
Energy	$0.07	0.13%
Labor	$0.98	2.84%
Capital	$3.63	6.80%
TOTAL =======>	$52.81	100%

Figure 16. SMC Sheet Line

PRODUCTION RATE

The sheet line production rate is specified by the linear output (ft/min), width of the sheet, and thickness of the sheet, all of which are assumed to be constant throughout the operation. These values are used to compute the output of the SMC line in lbs/hour ("Productivity While Running"). Productivity While Running (PwR) is the rate at which the line produces sheet when it is running, and is computed as:

PwR = Feed Rate * Width * Thickness * Specific Gravity

"Effective Production" is the daily output of the sheet line, accounting for unproductive time including:

1. scheduled downtime necessary to perform routine maintenance, such as cleaning of the equipment;
2. unscheduled downtime due to breakage of the equipment; and
3. unproductive time due to exogenous factors, such as poor market conditions for SMC products.

MATERIAL COST

Material cost is that portion of the total cost of producing sheet which is attributable to the material itself. The "material" is composed of paste

(paste = resin + filler + additives) and reinforcement. Separate scrap rates for the paste and finished sheet are used, and their default values were obtained from Navistar.

ENERGY COST

Energy costs are derived from an estimate of the percentage of the rated horsepower of pumps, mixers, etc., that is actually delivered to the process, plus an estimate of the power consumed in lighting, controls, etc. Energy costs are distributed over the "Effective Productivity", and are negligible in the present operation.

LABOR COST

Labor Cost (LC) is computed as:

LC = Wage * Number of Laborers / Productivity

The cost of fixed labor is distributed over the "Effective Productivity", whereas variable labor is distributed over the "Productivity When Running" (i.e., it is assumed that variable labor can be utilized elsewhere during unproductive time).

CAPITAL COSTS

Capital costs are estimated using the capital recovery factor, as discussed in the injection molding model. The total capital investment is spread over a number of years (default 5) assuming a fixed interest rate (default 12%), and is further distributed over the annual production volume.

The total capital investment is estimated from the sum of the cost of the individual pieces of equipment used in the process. Additionally, a fixed percentage for auxiliary equipment (default 5%) and installation (default 33%) is added to this total.

SUMMARY OF SHEET LINE COSTS

A summary of the costs of materials, energy, labor, and capital per pound of SMC sheet produced is presented at the bottom of the "Sheet Line" analysis. This summary can be seen in Figure 16 on page 118, as estimated by the model for the first low profile formulation of SMC.

SHEET MOLDING INPUTS

In the "Sheet Molding Inputs" section, the user supplies parameters which define the component that is to be molded. Additionally, this section contains default data which define the economic environment and the processing parameters for the SMC operation. In contrast to the "Sheet Line" section,

the data values and functional relationships between processing parameters are based on industry average values obtained from a number of plants. A set of molding inputs, taken from a case study of the cost of molding an automotive hood outer, is presented in Figure 17 on page 123.

In the following pages, the molding input parameters are discussed in the order in which they appear in Figure 17 on page 123. Only those parameters which are not self explanatory, or which are not directly analagous to inputs to the injection molding model, are discussed.

COMPONENT SPECIFICATIONS

1. Formulation Number: carried forward from the selection made in the "Formulations" column.
2. Maximum Wall Thickness: twice the distance from the point in the solid SMC which is farthest from the nearest wall to the nearest wall; for flat sheet, the thickness of the sheet. This parameter defines the point in the component which heats most slowly, and is used in the cycle time estimation.
3. Total External Surface Area: the surface area of one side of the mold cavity. The ratio of Total External Area to Projected Area is always greater than or equal to one. This ratio is used as a measure of the "complexity" of the component.

COMPONENT SPECIFICATIONS

Formulation Number	2	
Weight	24.75	lbs.
Maximum Wall Thickness	0.145	in.
Projected Area	2888	sq in
Total External Surface Area	3255	sq in

OTHER INPUTS

Annual Production Volume	40	(000/yr)
Number of Cavities	1	
Length of Production Run	3	yrs.
Scrap Rate (%)	6.0%	
Cycle Time <optional>	0	sec.
Tool Cost/Set <optional>	0	($000/set)
Sheet Cost <optional>	$0.00	/lb
Press Tonnage <optional>	0	tons
Dedicated Molding Equipment	0	(1=yes, 0=no)

EXOGENOUS COST FACTORS

Direct Wages (w/ benefits)	$13.00	/hr.
Working Days/Yr.	240	
Working Hours/Day	16	
Capital Recovery Rate	12%	
Price, Building Space	$75.00	/sq ft
Price of Electricity	$0.080	/kwh

PROCESS RELATED FACTORS

Machine Cost Coefficient	$8,621	
Machine Cost Scaling Exponent	0.567	
Accounting Life of Machine	6	yrs.
Direct Laborers Per Machine	2	
Mold Cost Coefficient	$19,308	
Mold Cost Scaling Exponent	0.76	
Baseline Physical Mold Life	800,000	cycles
Internal Molding Pressure	1500	psi
Auxiliary Equip. Cost (% mmch)	30.0%	
Installation Cost (% mmch)	10.0%	
Overhead Burden (% fc)	35.0%	
Productive Time (% avail. time)	80.0%	
Cycle Time (intercept)	50	sec.
Cycle Time Scaling Factor	250	sec/in
Electrical Heat	0.50	kWh/lb
Electrical Mechanical Energy	0.08	kW/press ton

Figure 17. Sheet Molding Inputs: Case Study - Automotive Hood Outer

OTHER INPUTS

Other Inputs include a variety of economic and processing parameters, several of which are marked "<optional>". If "0" is entered for any of these parameters, its value is estimated by the model. Otherwise, the value that is input is used in the calculations.

1. Sheet Cost: If the sheet cost is entered as an optional user input, the "Formulation" and "Sheet Line" estimations of sheet cost are overridden. However, the "Mold Life" and "Cycle Time Adjustment Factors" for the selected formulation are still used in the estimation.

PROCESS RELATED FACTORS

"Process Related Factors" are used to estimate capital investment costs, overhead costs, and certain of the technical process variables (e.g., cycle time). Additionally, these factors underlie the capital accounting system of the model. For a more complete understanding of these parameters, refer to the following section on "Molding Cost Estimates".

Specific comments on "Process Related Factors" are:

1. Machine Cost Coefficient & Scaling Exponent: statistically determined parameters which are used to estimate the capital investment cost of the molding equipment as a function of the "Press Tonnage".
2. Mold Cost Coefficient & Scaling Exponent: statistically determined parameters which are used to estimate the capital investment cost in tooling as a function of component weight and "Mold Complexity Ratio" ("Total External Surface Area" / "Projected Area").
3. Internal Molding Pressure: a process parameter which is multiplied by the projected area of the part to determine the tonnage of the molding press.
4. Cycle Time Intercept and Scaling Factor: statistically determined parameters which are used to estimate the cycle time as a function of "Maximum Wall Thickness".
5. Electrical Heat and Mechanical Energy: process parameters used to estimate utilities costs as a function of part weight and press tonnage.

MOLDING COST ESTIMATE SECTION

Molding cost estimates are generated from the information input in the "Sheet Molding Inputs" section. The elements of the estimate are separated into two categories; variable and fixed. Each element is presented on three bases: $/piece, $/year, and percent of total cost. Additionally, for those cost elements which involve a capital investment, this value is also

provided. The estimate that results from the inputs in Figure 17 on page 123 is presented in Figure 18 on page 127.

VARIABLE COSTS

Three variable cost elements are estimated in this section of the model: material cost, utilities cost, and direct labor costs. Only the formula for the utilities cost is presented below. The other variable cost elements are estimated with formula analagous to those presented in "Variable Cost Elements" on page 73.

While the equation for estimating materials cost is the same in both the injection molding and SMC models, the source of material price is different. In the SMC model, the cumulative costs of the "Sheet Line" become the raw material price for sheet molding, unless an optional price is specified by the user. In the injection molding model, materials prices are taken from the materials database.

VARIABLE COST ELEMENTS	$/piece	$/year	percent
Material Cost	$14.05	$561,802	58.0%
Utility Cost	$1.48	$59,125	6.1%
Direct Labor Cost	$1.17	$46,719	4.8%
TOTAL VARIABLE COST ===>	$16.69	$66[illegible],64[illegible]	68.9%

FIXED COST ELEMENTS	$/piece	$/year	percent	investment
Main Machine Cost	$1.31	$52,505	5.4%	$673,236
Tooling Cost	$2.02	$80,773	8.3%	$242,320
Overhead Labor Cost	$1.43	$57,254	5.9%	
Building Cost	$0.19	$7,726	0.8%	$154,517
Installation Cost	$0.13	$5,251	0.5%	$67,324
Auxiliary Equipment Cost	$0.39	$15,752	1.6%	$201,971
Maintenance Cost	$0.04	$1,575	0.2%	
Cost of Capital	$2.01	$80,242	8.3%	
TOTAL FIXED COST ===>	$7.53	$301,078	31.1%	
TOTAL FABRICATION COST ===>	$24.22	$968,724	100.0%	

ADDITIONAL INFORMATION	
Sheet Price	$0.53 /lb
Approximate Part Density	1.5 g/cc
Man-Hours Direct Labor	3594 /yr
Number Direct Laborers/Shift	2
Cycle Time	129.4 sec
Number of Parallel Streams	0.467936
Run-Time for One Machine	47%
Physical Mold Life	800000 cycles
Productive Mold Life	3.00 yrs
Required Building Space	2060 sq ft
Mold Complexity Ratio	1.1
Press Tonnage	2165.625
Sheet Line Utilization	12.1%

Figure 18. SMC Cost Estimate: Case Study - Automotive Hood Outer

UTILITY COST

The cost of energy is estimated as:

UC = $/kWh * ((Weight * kWh/lb) + (Ton * C-time * EME))

$/kWh = Price of Electricity
kWh/lb = Process Related Factor
Ton = Press Tonnage as estimated in Additional Information
C-time = Cycle Time as estimated in Additional Information
EME = Electrical Mechanical Energy, a Process Related Factor

FIXED COSTS

Formulae for the primary basis of the fixed cost elements are presented below.

MAIN MACHINE COST

The capital investment in the main machine, which includes the cost of the press, hydraulic circuit, pump, and control panel, is computed based on "Press Tonnage" according to the following equation:

$$MMC = (\$8,621 * \text{Press Tonnage})^{0.567}$$

The "Machine Cost Coefficient" (default $8,621) and "Exponent" (default 0.567) were determined from regression analysis, using data obtained from

press manufacturers, principally Williams & White (26). These values reflect the cost of conventional equipment, and would not apply for extreme levels of specialization.

The "$/year" basis for main machine cost is computed from the "investment" basis by multiplying by the "Number of Parallel Streams" and dividing by the "Accounting Life of Machine" (default 6 years). If dedicated equipment is assumed, the number of parallel streams is the minimum whole number of machines required to produce the annual production volume. If non-dedicated equipment is assumed, fractional parallel streams are allowed.

TOOLING COST

The capital investment in tooling is estimated by the following equation:

$$TC = \$19{,}308 * (Wgt * Cav * AT/AP)^{0.76}$$

Wgt = Weight of the Component
Cav = Number of Cavities in the tool
AT = Total Surface Area of the Component
AP = Projected Area of the Component

The "Tooling Cost Coefficient" (default $19,308) and "Exponent" (default 0.76) were determined from regression analysis, using data obtained from various molders of SMC parts, including General Electric (27), General

Motors (28), DiversiTech General (29), Molded Fiber Glass Companies (30), and Owens-Corning (31).

The "$/year" basis for tooling cost is computed in the same manner as for main machine cost, except that only whole numbers of tools are allowed.

OTHER FIXED COST ELEMENTS

The remaining fixed cost elements are analagous to elements of the injection molding model, and are estimated by the same set of equations. The interested reader is referred back to the section "Fixed Cost Elements" on page 76.

ADDITIONAL INFORMATION

The "Additional Information" section provides estimates of various economic and processing parameters which are related to the cost estimation. This information may be reviewed by the user to determine the validity of the cost estimates. If there are any values which seem inappropriate, a change should be made to the input assumptions (or equations) of the model. Thus, using the model may be an iterative process, involving reviewing the "Additional Information", changing certain input assumptions, and recalculating the results.

APPROXIMATE PART DENSITY

Approximate Part Density is estimated by the following equation.

APD = Wgt / (Total External Area * Max. Thickness)

"Approximate Part Density" is used as a safety check to verify that weight, surface area, and thickness are appropriately specified. The specific gravity of most SMC parts ranges between 1.8 and 2.4. If the APD is significantly outside of this range, there may be reason to suspect that the user-specified weight, area, and maximum thickness are not consistent. However, since the maximum thickness may be significantly different from the average thickness, the 1.8 to 2.4 range can only be used as a guideline.

CYCLE TIME

Cycle time is either provided as an optional input by the user, or it is estimated by the equation:

CT = (50sec + 250sec/in * Max. Thickness) * Mtl Adj

Mtl Adj = material adjustment factor for selected formulation

The 50sec and 250sec/in parameters were obtained from regression analysis of case study data obtained from various molders of SMC parts, including

General Electric, General Motors, Budd Co., Ford, DuPont, and Owens-Corning. Materials adjustment factors were obtained as qualitative estimates from the same sources.

SHEET LINE UTILIZATION

"Sheet Line Utilization" is the fraction of the sheet lines's working year spent producing sheet for the component being molded. It is estimated from the ratio of the pounds per hour consumed by the molding operation divided by the pounds per hour output by the sheet line. The equation for "Sheet Line Utilization" is:

$$SU = Wgt * Cav * Nmch / (C\text{-}time/Prd) / \text{Line Effective Productivity}$$

Wgt = Weight of the Component
Cav = Number of Cavities in the tool
Nmch = Number of Parallel Streams
C-time = Cycle Time
Prd = Molding Process Productivity

For most production runs, the "Sheet Line Utilization" is a small fraction, typically less than 20%. Thus, one sheet line can supply raw SMC sheet to many molding presses and for many different component runs. If this were not so, simple coupling of the sheet line with the molding operation through the cost of the sheet would not be reliable. When line utilization approachs or exceeds 100%, the cost of making the sheet changes, since a second parallel sheet line is required. This economic feature is not captured by simple cost coupling. Also, the issues of how to account for the

cost of the lines and whether or not the lines are dedicated to the component production run arise when more than one line is required.

OTHER ADDITIONAL INFORMATION ITEMS

The remaining "Additional Information" items are computed from the same bases used in the injection molding cost model. These items are described in "Additional Information" on page 89.

SUMMARY OF THE SMC COST MODEL

The SMC process is modeled as two separate operations, coupled through the cost of the raw SMC sheet. The first operation, the sheet line, entails the production of SMC sheet. This sheet becomes an input to the second operation, sheet molding. The cumulative costs of making the raw sheet are a cost factor input to the molding operation.

Coupling processes through their costs is one of the simplest methods for linking the stages of a manufacturing sequence. Effectively, each process is modeled as a stand-alone, with its output becoming the input to the next process. A comparison of this method with a more complex means of coupling processes is provided in the following section on the filament winding cost model.

In the SMC model, the costs of each operation are estimated by the technical cost method. Costs are broken down into constituent elements,

and these elements are estimated separately. Wherever possible, engineering knowledge is brought to bear on the estimation of each element. Like the injection molding model, the SMC model is the synthesis of these elemental cost estimations into a consistent framework.

FILAMENT WINDING COST MODEL

The filament winding cost model is similar to both the injection molding and SMC cost models in terms of scope and methodology. For this reason, the discussion regarding definitions of factor inputs and estimating equations has been abbreviated. Rather, the intent of the following description is to provide an overview of the model, and to focus attention on the principal difference between this model and the two preceding ones.

FILAMENT WINDING MODEL STRUCTURE

The filament winding cost model is structured in four sections: a parameter input section, an internal database of cost parameters, a section for computation of the costs associated with winding, and a final section for estimating the costs of curing the wound structure. The method of coupling the winding and curing operations is the principal difference that distinguishes this model from the preceding ones.

The inputs that are supplied to the filament winding model are presented in Figure 19 on page 136. The input values shown are from a case study of the cost of winding pipe to be used in transporting acidic or oxidative liquids. Specifically, the pipe example is for 10 feet of 6 inch diameter PolyThread® pipe produced by A.O. Smith/Inland (32). This pipe is for service not exceeding 200 F and at pressures not exceeding 125 psig. The price of this pipe is $12/ft or $120 for a 10 foot length.

COMPONENT SPECIFICATION	
Weight	24 lbs
Length	120 in
Average Diameter	6.5 in
Maximum Wall Thickness	0.138 in
Void Content	5.0%
Average Winding Angle (+/-)	64 degrees
Filament Percent	50.0% by vol
Resin <menu>	6
Filament <menu>	1
Or, Prepreg <menu>	0
Mandrel Technology <menu>	1
Annual Production Volume	5 000/yr
Length of Production Run	5 yrs
WINDING PARAMETERS	
Setup Time	15 min
Tow or Tape Run-out Rate	80 FPM
Maximum Winding Speed	60 RPM
Number of Spools or Rolls	24
Productivity (% of available time)	70.0%
Or, Cycle Time <optional>	0 min
EXOGENOUS COST FACTORS	
Working Days/Yr.	240
Working Hours/Day	8
Direct Labor Wages (w/benefits)	$12.50 /hr
Accounting Life of Equipment	5 yrs
Price, Building Space	$80.00 /sq ft
Building Recovery Life	20 yrs
Price of Electricity	$0.080 /kWh
Capital Recovery Rate	10%
Working Capital Period	3 mos
Dedicated Equipment	0 (1=y,0=n)

Figure 19. Inputs to the Filament Winding Cost Model

The internal database of cost parameters consists of five separate menus, namely resins, filaments, prepregs, geometries, and mandrel types. Associated with each menu entry, there is a record of information relating to that entry. These menus are not shown, but are similar in construct and purpose to the menus used in the injection molding and SMC models. The data fields in these menus are:

1. Resins Menu
   a. Name - The trade name and grade of a specific winding resin and all associated curing agents, inhibitors, etc.
   b. Price - The price in $/lb for that resin.
   c. Cure Temperature - The manufacturers recommended cure temperature.
   d. Cure Time - The approximate time required to cure the resin before further processing.
2. Filaments Menu
   a. Name - The trade name and grade of a specific filament.
   b. Price - The price in $/lb for that filament.
   c. Cross Section - The solid cross sectional area for the filament tow, usually estimated from the average diameter of the fibers and from the tow count (the number of fibers in the tow).
3. Prepregs Menu
   a. Name - The descriptive name of the resin/filament combination comprising the prepreg tape.
   b. Cross Section - The solid cross sectional area of the prepreg tape.

c. Cure Temperature - The manufacturers recommended cure temperature.

d. Cure Time - The approximate time required to cure the resin before further processing.

4. Mandrels Menu

a. Name - The descriptive name of the mandrel technology.

b. Material Price - The price in cents per cubic inch of the primary material(s) of construction for the mandrel.

c. Thickness - The average wall thickness of the mandrel.

d. Fabrication Multiplier - The multiplier that, when multiplied by the material cost, yields an estimate of the finished cost of the mandrel.

e. Life - The number of times that the mandrel can be used before it is worn out. For mandrel technologies where the mandrel becomes an integral part of the finished component, the life is one.

In addition to the input data shown in Figure 19 on page 136 and the data associated with the five menus, a sixth data set that contains processing parameters is included in the model. These data provide the basis for estimating equipment costs and processing rates. They are analagous to the "process related parameters" described for the injection molding model.

FILAMENT WINDING MODEL SAMPLE RESULTS AND DISCUSSION

The results from the wound pipe case study, showing the costs of winding and curing and summarizing total costs, are presented in Figure 20 on page 140, Figure 21 on page 141, and Figure 22 on page 142.

The winding and curing costs are estimated by the technical cost method which was described in detail for both the injection molding and SMC cost models. While the equations used to estimate the individual elements differ from one model to another, the methodology is essentially the same. Total cost is estimated as the sum of individual cost elements, each of which is estimated from engineering considerations. The elements of cost are the material, energy, labor, machinery, tooling, etc. For each of these, an equation is derived that relates the cost of that element to other factors such as the design specifications, processing parameters, costs of input factors, etc.

The filament winding model is similar to the SMC model in the respect that both involve two sequential process operations. The key distinction between the filament winding and SMC models is the method of coupling these operations. For SMC, the operations (sheet making and sheet molding) are cost coupled, with the output of the first becoming a cost factor input to the second. For filament winding, the operations are rate coupled, as described in the following section.

VARIABLE COST ELEMENTS	$/piece	$/year	percent
Material Cost	$21.01	$105,059	47.9%
Energy Cost	$0.77	$3,840	1.8%
Direct Labor Cost	$12.35	$61,743	28.2%
TOTAL VARIABLE COST ===>	$34.13	$170,642	77.8%

FIXED COST ELEMENTS	$/piece	$/year	percent	investment
Main Machine Cost	$1.97	$9,853	4.5%	$41,034
Mandrel Cost	$0.97	$4,870	2.2%	$937
Overhead Labor Cost	$1.48	$7,397	3.4%	
Building Cost	$1.13	$5,650	2.6%	$113,008
Installation Cost	$0.39	$1,971	0.9%	$8,207
Auxiliary Equipment Cost	$0.49	$2,463	1.1%	$10,259
Maintenance Cost	$0.24	$1,196	0.5%	
Cost of Capital	$3.03	$15,156	6.9%	
TOTAL FIXED COST ===>	$9.71	$48,556	22.2%	$208,792
TOTAL FABRICATION COST ===>	$43.84	$219,198	100.0%	

ADDITIONAL INFORMATION	
Material Price (w/scrap)	$0.88 $/lb
Approximate Wound Density	1.97 g/cc
Winding Time	19.4 min
Cycle Time	27.7 min
Winding Speed	42.3 RPM
Winding Rate	74.4 lb/hr
Run-Time for One Machine	120%
Number of Parallel Streams	1.2
Required Building Space	1413 sq ft

Figure 20. Cost of Winding Pipe

VARIABLE COST ELEMENTS	$/piece	$/year	percent
Material Cost	$0.00	$0	0.0%
Energy Cost	$2.40	$11,983	41.2%
Direct Labor Cost	$1.37	$6,868	23.6%
TOTAL VARIABLE COST ===>	$3.77	$18,851	64.8%

FIXED COST ELEMENTS	$/piece	$/year	percent	investment
Main Machine Cost	$0.95	$4,760	16.4%	$41,582
Building Cost	$0.54	$2,694	9.3%	$53,875
Auxiliary Equipment Cost	$0.14	$714	2.5%	$6,237
Cost of Capital	$0.41	$2,061	7.1%	
TOTAL FIXED COST ===>	$2.05	$10,229	35.2%	$81,244
TOTAL CURING COST ====>	$5.82	$29,080	100%	

ADDITIONAL INFORMATION

Cure Time	2 hrs
Cycle Time	2.86 hrs
Cure Cycle Max. Temperature	85 C
Parts Cured Concurrently	13
Run-Time for One Machine	57%
Number of Parallel Streams	0.6
Required Building Space	673 sq ft
Total Oven/Autoclave Cap.	120 cu ft

Figure 21. Cost of Curing Pipe

	$/piece	$/year	percent
Material Cost	$21.01	$105,059	42.3%
Energy Cost	$3.16	$15,823	6.4%
Direct Labor Cost	$13.72	$68,611	27.6%
Fixed Costs	$11.76	$58,785	23.7%
TOTAL COST =====>	$49.66	$248,277	100%

ADDITIONAL INFORMATION	
Total Capital Investment	$290,036
Mandrels for Production Run	26

Figure 22. Summary of Winding and Curing Costs for Pipe

COUPLING THE WINDING AND CURING OPERATIONS

The winding and curing operations are coupled together through their respective rates. The reason for coupling them in this manner is that curing often takes more time than winding and can constrain the rate at which components are produced. This constraint is most apparent when considering reusable mandrels. In these instances, a second part cannot be wound until the mandrel is extracted from the preceding cured part. Even when the mandrel remains integral to the component (e.g., aluminum liners in pressure vessels), the rate of winding cannot exceed the rate of curing, since it is not accepted practice to store large numbers of uncured parts.

The filament winding cost model accounts for rate coupling between winding and curing. The methods and equations for accomplishing this are described below. However, first, the equations used to estimate the "natural" rates of the winding and curing operations are described. The "natural" rates are defined as the rates that would be expected if each of these processes operated independently of the other. The "natural" rates form the basis for coupling the operations.

WINDING RATE

The rate of the winding operation (i.e., its cycle time) is either specified directly by the model's user, or it is estimated by the equations shown in Figure 23 on page 144.

These equations estimate winding time by dividing the volume of material to be wound (cubic inches) by the volumetric winding rate (cubic inches per minute). The volume of material to be wound is estimated from the design specifications of the component (i.e., its length, diameter, and wall thickness). The volumetric winding rate is estimated from the product of the linear feed rate and cross-sectional area of the winding band. A separate algorithm checks to see that the rotational winding speed does not exceed a specified maximum number of revolutions per minute. If it does, the linear feed rate is reduced proportionately. The "Effective Winding Time" is estimated by dividing the winding time as estimated above by the "Process Productivity".

```
Winding_Time = Wound_Volume / Volumetric_Winding_Rate + Setup_Time

  Wound_Volume = Pi * Diameter * Length * Thickness

  Volumetric_Winding_Rate = Feed_Rate * X-Section

  Feed_Rate = a specified process parameter from the model's inputs, or

  Feed_Rate = Max_RPM * Pi * Diameter * X-Section / SIN(Avg_Wind_Angle)

  X-Section = (pi/4)/(%Filmt) * Filament_Area * No_Spools/(1-%Void), or

  X-Section = Database Value for Prepregs

    Setup_Time:  the specified time requirement for setting up the
                 mandrel prior to winding.

    Max_RPM:  the maximum speed in revolutions per minute that the
              machine is allowed to turn due to safety concerns and/or
              limitations of the winding equipment.

    Avg_Wind_Angle:  the average angle formed between the filaments and
                     the center line of the mandrel.

    %Filmt:  the specified precent by volume of filaments in the final
             wound structure.

    Filament_Area:  solid cross-sectional area of the filaments in the
                    or tape (i.e., tow count * square area of one
                    filament), tabulated in the filament menu database.

    No_Spools:  the number of spools of filaments or prepreg tapes that
                are wound simultaneously onto the mandrel.

    %Voids:  the specified void content in the final wound structure.
```

Figure 23. Filament Winding Cycle Time Equations

An equation is used to estimate the cross-sectional area of the band when a filament and resin are specified (rather than a prepreg). This equation employs an assumption that can be described as "simple-cubic packing of filaments". Filaments are modeled as circular columns, and surrounding each filament, there is a square prism of space that can be filled with resin without expanding the cross-sectional area of the band. (This assumption can be visuallized by considering a full jar of uncooked spagetti, into which an amount of liquid can be poured without overflowing the container.) The most significant implication of this assumption is that a wound structure can be up to 22% resin by volume, without expanding the cross-sectional area of winding band.

CURING RATE

The time requirement for curing is taken from the resin or prepreg properties databases, depending on which type of material is being wound. This approach attributes all of the time requirement to the reactivity of the matrix material, and neglects any effect that may arise from the geometry of the part.

RATE COUPLING THE WINDING AND CURING OPERATIONS

The winding and curing operations are coupled within the model on the basis of four rules, namely:

1. The overall rates of winding and curing must be equal,
2. Winding and curing are conducted concurrently, not sequentially,
3. Winding is the rate setting operation, and
4. All heat-cured parts in a production run are cured in the same autoclave or oven.

The implications of these rules are discussed in the following paragraphs for three possible scenarios. The first scenario is where winding requires less time than curing, as is typical of most filament wound applications, including most pipe and pressure vessels. In the second scenario, curing is faster than winding. The final scenario is the situation where the "natural" rates of winding and curing are equivalent.

1. Scenario One, Winding Faster than Curing: For the first scenario, to make the overall rates equal, the effective rate of curing must be increased. However, the absolute curing rate is fixed by the selection of the resin or prepreg system, and cannot be adjusted arbitrarily. To effectively speed up the rate of curing, it is assumed that multiple sets of mandrels are wound sequentially, and then cured concurrently. By curing several mandrels at the same time, the effective rate of curing, measured in parts cured per hour, is increased.

   The number of mandrels that must be cured concurrently in order to match the overall rates is estimated by the model. The consequence of using multiple mandrels is that it increases the capital investment,

not only for the multiple mandrel sets, but also for the larger sized ovens or autoclaves that are required to cure parts concurrently. Both of these consequences increase the piece cost of the finished parts.

For the filament wound pipe case study, the "natural" winding rate, including setup and productivity losses, is estimated to be 27.7 minutes per pipe per winding station. To produce the annual volume (5000/yr) at this rate, two winding stations are required. Therefore, the overall rate of winding is 13.8 minutes per pipe.

The curing time is 2 hours, which when divided by 70% process productivity yields an estimated 171 minutes per cure cycle. The ratio of this rate to the winding rate defines the number of parts cured concurrently. In this case, 13 pipes are cured concurrently. By curing 13 parts in 171 minutes, the overall curing time becomes 13.2 minutes per pipe - equivalent to the rate of winding.

To cure 13 pipes concurrently requires that a minimum of 26 mandrels are available. A double set of mandrels is required so that the winding operation can continue while one set of mandrels is being cured, in keeping with the second rule for coupling the processes. With each mandrel costing $937, the total investment in mandrels is $24,362.

2. Scenario Two, Curing Faster than Winding: For the second scenario, when curing is "naturally" faster than winding, the overall rate of the curing operation must be reduced. However, again, the actual time required for curing cannot be reduced arbitrarily. Instead, the rate

must be reduced by adding idle time to the curing operation. The basis for accounting for the cost of this idle time depends upon whether or not dedicated equipment is assumed.

If dedicated equipment is assumed, than the cost of idle time is accounted by distributing the total annual capital investment in curing equipment onto the annual production run. If it is assumed that the equipment is not dedicated, than the idle time does not add to the total cost, since it is assumed that the ovens/autoclaves are used for curing other parts during these idle periods.

3. Scenario Three, Winding and Curing Rates Equal: For the third scenario, where the rates are "naturally" equivalent, adjustments to the modeling basis are not required except when multiple winding stations are involved. If only one winding station is involved, it is assumed that components are cured one at a time and that a total of two mandrels is required, one for winding and one for curing. If two winding stations are involved, components are cured two at a time (in one oven), and a total of four mandrels is required.

SUMMARY OF THE FILAMENT WINDING MODEL

The filament winding cost model uses the technical cost method to estimate the costs of the winding and curing operations. The elements of cost are divided into two categories, variable costs and fixed costs. Total cost is

estimated as the sum of these individual cost elements, each of which is estimated from an equation that relates the cost of that element to other factors such as the design specifications, processing parameters, costs of input factors, etc. In this respect, the filament winding model is similar to both the previously described injection molding and SMC cost models.

The filament winding model is similar to the SMC model in that each involves estimating the costs of two operations. For SMC, these operations are sheet making and sheet molding. For filament winding, the operations are winding and curing. The distinction between the models is the method of linking the first operation to the second.

In the SMC model, the sheet making operation is linked to the sheet molding operation through the cost of the sheet. The sheet making calculations yield an estimate of the cost of a pound of raw SMC sheet, and this value becomes an input parameter to the sheet molding operation. The cost of the sheet is the only linkage between two otherwise independent operations.

In the filament winding model, the linkage is more complex. Four rules define the linkage between the winding and curing operations. Because of these rules, the cost of winding depends on the "natural" rate of the curing operation, and vice versa. The operations are intimately linked and cannot be considered separately.

The rules for linking the winding and curing operations were derived through conversations with people involved in the filament winding business (33). While these rules are representative of many filament winding

projects, they are not absolute. Specifically, neither the rule that winding is the rate setting operation nor the rule that all heat-cured parts are cured in a single oven/autoclave hold in all situations. Also, the rule that requires winding and curing to be concurrent, rather than sequential, does not generally hold for small production runs or prototype windings.

Rules that link winding and curing are required because of the relationship between these operations. First, all parts that are wound must be subsequently cured, resulting in a one-to-one relationship between the overall rates of these operations. This situation does not exist for SMC, where the sheet making line may be used to supply raw material to several molding operations or to an external market for raw SMC sheet.

A second factor linking the filament winding operations is that, as modeled, the mandrels used in winding are also used for curing. Thus, the operations share common equipment, and therefore, share a cost element. Again, for the SMC process as modeled, this is not true.

The physical relationships between winding and curing described above preclude modeling filament winding on the basis of the simpler cost linkage used in the SMC model. A simple cost linkage is appropriate only when the operations that are being linked are physically independent.

SUMMARY AND CONCLUSIONS

The technique of technical cost modeling was discussed. Three processes and three case studies were presented - injection molded waste bin, SMC automotive hood outer, and filament wound chemical pipe. The case studies were selected from among many cost analyses that have been conducted over the course of this research. The three models were selected from among ten plastics and composites fabrication models that were also developed in this time frame (34).

The technical cost method was used in constructing each of these process cost models. In this methodology, the costs of a process are divided into two categories, variable costs and fixed costs. Each categories is further subdivided into cost elements, and each element is estimated separately. The equations for estimating the cost elements are based on theoretical considerations, engineering judgments, and statistically derived relationships. A technical cost model results from the synthesis of these equations into a computerized framework.

The cost models are presented in order of increasing computational complexity. The first process model, injection molding, considers a one step, stand-alone operation. The costs of this operation are estimated directly, and they are independent of external influences.

The SMC process is modeled as two separate operations. These operations are linked together by a shared cost factor. The first operation involves production of raw SMC sheet. The cost of this sheet becomes an input to the second operation.

Coupling processes through their costs is one of the simplest methods for linking the stages of a manufacturing sequence. Effectively, each process is modeled as a stand-alone, with its output becoming an input to the next process. This approach is roughly equivalent to assuming that a market exists for the intermediate product, and that the demand for this product is independent of the next operation.

The filament winding model is similar to the SMC model in that it involves estimating the costs of two operations. However, in the filament winding model, the linkage is more complex. Four rules define the linkage, and because of these rules, the cost of the second operation depends on the rate of the first operation, and vice versa. The operations are intimately linked and cannot be considered separately.

Technical cost models demonstrate the advantages of combining engineering estimations with a disciplined economic assessment of a manufacturing process. Even though these models are inevitably based on simplifying assumptions, their accuracy generally exceeds that of the more common cost estimating techniques. Additionally, the technical cost approach provides greater insight into the nature of the factors and relationships that contribute to cost.

Estimating piece costs is one capability of technical cost models. However, it is the framework for estimation that provides the greatest benefit. The discipline enforced by the framework upon the cost estimating process leads to consistent and easily justifiable cost estimates. Fur-

thermore, the consequences of uncertainty can be evaluated with this framework through sensitivity analyses.

To draw conclusions from this research is difficult, because the cost models that are presented herein are neither exact nor complete; nor by their nature, can they ever be. In one sense, each equation for estimating a process parameter or cost element represents a specific, though small, conclusion of this research. In this respect, that the cycle time of injection molding is related to the theoretical cooling time and the weight of the molded part according to the equation presented in "Total Cycle Time" on page 96 is one specific conclusion.

A more global conclusion of this research is that the technical cost method of cost estimation is valid. At the outset of this research, many of the individuals referenced in the bibliography openly doubted the methodology. They felt the interactions among processing parameters and cost elements were too complex to model. While many of these interactions are still not captured completely, the models are being used by industry for cost estimation, indicating practical validity to the approach.

FUTURE WORK

Although not included in this thesis, technical cost models have been developed for other plastics and composites fabrication processes. Processes that could be modeled in the future include resin transfer molding, injection blow molding, structural RIM molding, co-injection molding, and coextrusion.

Additionally, there are derivatives for the processes that have been modeled that are not addressed by the models, as they exist. For instance, it is not possible to estimate the cost of molding-in inserts with the current version of the injection molding model; nor has data been collected for assessing the impact of these inserts on cycle time.

The databases in the models can always be expanded to include more resins, geometries, filaments, mandrel types, etc. Additionally, both the economic and process related parameters in the models need to be updated on a regular basis, as their values are subject to change. Expanding and updating each model within its existing framework represents an unbounded amount of potential future work.

Finally, more work is suggested in the area of operations coupling, expanding on the analysis presented in the filament winding model. The rules that are used to link the winding and curing operations constitute one of many possible sets of coupling rules. In other manufacturing processes, these rules would not be appropriate. For instance, manufacturing that involves in-line inventories or "stores" of semi-finished products, require a different set of coupling rules. Assessing the cost of invento-

ries by the technical cost method requires a set of decision rules that allows for their existence in the manufacturing process.

The ultimate extension of the technical cost method would entail modeling, in a robust sense, the set of coupled operations required to produce, for instance, automobiles. A great deal of future work is required before this goal is realized.

APPENDIX A. BATTENFELD MACHINE COST DATA

Clamp Force (kN)	Price (DM)	Clamp Force (tons)	Price ($)	Price* ($)
100	47380	11.2	$21,834	$18,976
200	53100	22.5	$24,470	$23,122
230	49530	25.9	$22,825	$24,365
250	59650	28.1	$27,488	$25,194
300	64380	33.7	$29,668	$27,267
300	67500	33.7	$31,106	$27,267
460	72430	51.7	$33,378	$33,900
500	86000	56.2	$39,631	$35,558
650	90650	73.1	$41,774	$41,776
700	104500	78.7	$48,157	$43,849
750	101070	84.3	$46,576	$45,922
750	155400	84.3	$71,613	$45,922
850	106300	95.5	$48,986	$50,067
1000	132400	112.4	$61,014	$56,286
1100	188100	123.6	$86,682	$60,431
1300	134800	146.1	$62,120	$68,722
1500	172300	168.6	$79,401	$77,013
1600	207600	179.8	$95,668	$81,158
1800	175400	202.3	$80,829	$89,449
2200	215000	247.3	$99,078	$106,031
2400	265000	269.8	$122,120	$114,322
2500	218200	281.0	$100,553	$118,468
3200	321000	359.7	$147,926	$147,486
4000	368500	449.6	$169,816	$180,650
5000	488000	562.0	$224,885	$222,105
5600	556200	629.4	$256,313	$246,978
8500	758100	955.4	$349,355	$367,197
10500	940400	1180.2	$433,364	$450,106
12500	1095400	1405.0	$504,793	$533,016
15000	1308800	1686.0	$603,134	$636,653
18000	1583600	2023.2	$729,770	$761,017
22000	2034900	2472.8	$937,742	$926,837
26000	2474800	2922.4	$1,140,461	$1,092,656
30000	2746600	3372.0	$1,265,714	$1,258,475

Currency Conversion: $0.46 /DM

Injection Molding Machine Cost Analysis

Regression Output:

Constant	$14,831
Std Err of Y Est	16177.82826
R Squared	0.997675011
No. of Observations	34
Degrees of Freedom	32
X Coefficient(s)	$368.82
Std Err of Coef.	3.147382728

APPENDIX B. CYCLE TIME AND MOLD COST DATA

Cycle Time Regression Analysis

ORDINARY LEAST SQUARES DEPENDENT VARIABLE IS CTIME
SAMPLE RANGE 1 - 25

	COEFFICIENT	STANDARD ERROR	T-STATISTIC
COOL	1.351707	.1710123	7.904153
WGTCAV	1.514167E-02	1.861256E-03	8.13519
CONST	8.87469	2.135622	4.155553

R-squared	.8974837	Mean of depend var	32.424
Adjusted R-squared	.8881641	Std dev depend var	18.20269
Std err of regress	6.08732	Residual sum	-3.19191E-06
Durbin Watson stat	1.730834	Sum squared resid	815.2201
F statistic	96.30004		

COVARIANCE MATRIX

COOL,COOL	2.924519E-02	COOL,WGTCAV	-1.056966E-04
COOL,CONST	-.2280227	WGTCAV,WGTCAV	3.464273E-06
WGTCAV,CONST	-1.178232E-03	CONST,CONST	4.56088

Tooling Cost Regression Analysis

ORDINARY LEAST SQUARES DEPENDENT VARIABLE IS TOOL
SAMPLE RANGE 1 - 30

	COEFFICIENT	STANDARD ERROR	T-STATISTIC
WGTCAV	6.607199	4.582395	1.441866
ACTION	16150.55	4838.034	3.338246
PAREA	12.70496	2.959276	4.293268
CONST	10173.92	2752.473	3.696285

R-squared	.7720318	Mean of depend var	29530.47
Adjusted R-squared	.7457277	Std dev depend var	19546.9
Std err of regress	9856.608	Residual sum	5.748648E-04
Durbin Watson stat	1.705502	Sum squared resid	2.525971E+09
F statistic	29.35033		

COVARIANCE MATRIX

WGTCAV,WGTCAV	20.99834	WGTCAV,ACTION	-8133.608
WGTCAV,PAREA	-10.39085	WGTCAV,CONST	-155.5478
ACTION,ACTION	2.340658E+07	ACTION,PAREA	4264.703
ACTION,CONST	-4224681	PAREA,PAREA	8.757316
PAREA,CONST	-3493.964	CONST,CONST	7576106

NOTE: All tooling cost coefficents divided by $30/hr to yield parameters on equivalent shop hours basis.

Appendix B. Cycle Time and Mold Cost Data

Name/Description	Material	k (W/C/m)	Cp (J/kg/C)	Density (g/cc)	T_Melt (C)	T_Mold (C)	T_Eject (C)	Weight (g)	P_Area (cm2)	Avg_Wall (mm)	Max_Wall (mm)	No.Cavs	Complex (At/Ap)	Action (y/n)	Cyc_Time (sec)	Tool Cost
5 Liter Waste Bin	LDPE	0.30	2300	0.923	220	40	55	1550	1216	2.4	8.1	1	5.75	0	39	$49,020
TV Housing	HIPS	0.17	1340	1.05	260	30	55	1550	500	4.5	5	1	6.56	0	80.3	$80,000
Turntable Mounting Plate	HIPS	0.17	1340	1.05	240	30	45	493	1024	3	3	1	1.53	1	66	$64,000
TV Housing Back Cover	HIPS	0.17	1340	1.05	260	30	45	1755	4080	3	3	1	1.37	0	53	$56,000
TV Housing Back Cover	HIPS	0.17	1340	1.05	200	30	45	975	1725	3	3	1	1.79	0	49.7	$40,000
Belt Sander Housing	PA/30% Glass	0.36	1600	1.35	260	70	85	397	220	3	3	1	4.34	1	60.5	$25,764
Copier Manifold	PES	0.19	1330	1.51	330	100	120	140	200	3	4	1	1.55	1	48.6	$23,680
Box End-Cap	HDPE	0.17	1680	0.905	260	25	32.5	20	100	1.3	1.5	8	1.70	0	21	$15,360
Dialysis Cap	ABS	0.17	1500	1.05	245	40	52.5	114.4	200	2.5	2.5	8	2.18	0	45.5	$15,200
Transfusion Cap	PVC	0.16	1400	1.3	150	20	32.5	29.2	40	1.5	2.5	4	3.74	0	41.2	$14,336
Plug	Acetal	0.31	1470	1.41	195	40	55	4.6	6	2	3.1	8	2.72	0	17.5	$12,000
Typewriter Hood	PC	0.23	1260	1.2	280	90	105	140.8	387	3	3	1	1.01	0	31	$8,000
Medical Stopper	ABS	0.17	1500	1.05	250	40	52.5	34	21.2	3.5	4.5	4	4.36	0	36.4	$7,372
Hay Pick	Acetal	0.31	1470	1.41	195	80	110	93	58	12	12	1	0.95	0	120	$4,176
Large Unibox	HDPE	0.36	2300	0.952	260	40	65	1140	1534	2.1	3.3	1	3.72	1	42.4	$50,420
Ten Liter Bucket	HDPE	0.36	2300	0.952	280	40	75	280	670	1.2	3.2	1	3.66	0	10.4	$11,204
25 Liter Ice Chest	HDPE	0.36	2300	0.952	240	40	65	800	1068	1.8	2.3	1	4.37	0	36	$36,415
35 cm Laundry Basket	HDPE	0.36	2300	0.952	280	40	55	170	946	1.3	1.7	1	1.45	0	18	$44,818
Freezerbox	HDPE	0.36	2300	0.952	280	30	50	39	1520	1.1	2.6	1	0.25	0	5.9	$44,818
Laundry Bin	HDPE	0.36	2300	0.952	270	40	65	453	1520	1.8	2.6	1	1.74	0	25.7	$36,415
60 cm Laundry Basket	HDPE	0.36	2300	0.95	280	40	55	660	2770	2.1	2.8	1	1.19	0	40.5	$64,426
Ice Chest Lid	LDPE	0.30	2300	0.917	220	40	55	18	136	1	1.8	1	1.44	0	6.5	$6,162
Round Bin	LDPE	0.30	2300	0.923	240	40	50	1465	2360	2	4.5	1	3.36	0	44	$33,613
Mobile Refuse Bin	PE	0.46	2300	0.95	270	40	50	2780	2460	2.8	6.3	1	4.25	1	62	$81,232
25 l. Ice Chest Handle	HIPS	0.17	1350	1.05	230	40	50	164	90	4	8	1	4.34	1	40.5	$16,807
45 l. Waste Bin Cover	HIPS	0.17	1350	1.05	250	40	50	244	1266	1.8	3	1	1.02	0	20	$30,812
45 l. Waste Bin Top	HIPS	0.17	1350	1.05	250	40	50	172	754	1.6	3	1	1.36	0	14.7	$22,409
Cake Dish	HIPS	0.17	1350	1.05	230	40	50	234	990	1.6	1.8	1	1.41	0	15.6	$16,807
Cutlery Tray	HIPS	0.17	1350	1.05	250	60	70	300	888	1.8	3	1	1.79	0	20	$22,409
Cake Dish Cover	HIPS	0.17	1350	1.05	260	60	70	290	802	1.8	2	1	1.91	0	15	$22,409
Packable Edge Box	HIPS	0.17	1350	1.05	250	50	60	87	345	1.5	2.5	1	1.60	0	11.8	$12,605
Food Storage Box Cover	SAN	0.13	1300	1.08	240	70	80	880	1326	2.8	3	1	2.19	0	40	$36,415
Cottonbox	SAN	0.13	1300	1.08	220	70	80	69	89	1.5	4	1	4.84	0	14.4	$9,604

BIOGRAPHICAL NOTE

I was born in 1956 in Ithaca, New York.

I attended public grammer and high schools in Tucson, Arizona, and in Auburn, Alabama, and spent two years in private school in Tarsus, Turkey.

My undergraduate degree is from Vanderbilt University in Nashville, TN. There, my major was Chemical Engineering, and I graduated with honors in 1979.

I worked for two years at Hamilton Standard in Windsor Locks, CT, as a materials engineer on the Shuttle space suit program.

In 1981, I was accepted to the Masters program at MIT. I received a Masters in Polymerics from the Department of Materials Science and Engineering in 1983, studying under Professor Joel P. Clark.

From 1983 until 1985, I was on the research staff at MIT, working for Professor Clark. In 1985, I was admitted to the Doctoral program, working in the Materials Systems Laboratory.

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