Submitted for publication to
Encyclopedia of Materials Science & Engineering,
Elsevier Science Pubs.

Process-Based Cost Modeling:

Understanding the Economics of Technical Decisions

RANDOLPH KIRCHAIN & FRANK R. FIELD III, MATERIALS SYSTEMS LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

INTRODUCTION

The field of engineering is rife with models and methods for modeling. Fueled by ever-accelerating computational horsepower, these models have provided invaluable insights into every aspect of technical inquiry. Presently, mathematical models allow designers to relate geometry and material to the physical properties of their product and manufacturing engineers to relate operating conditions to the physical characteristics of process outputs.[1] In both cases, models allow controllable parameters to be fine-tuned using analytical methods rather than through time-consuming and potentially expensive experimentation and prototyping. Ideally, this capability allows decisionmakers to understand the physical consequences of their technical choices *before* those choices are put into action.

It is well recognized that manipulating design specifications or process operating conditions has consequence not only on product performance, but also on production costs. Furthermore, these costs must be considered when evaluating any change to product or process, because, ultimately, they establish the profit margin which a firm can realize. It is no secret that a firm remains a going concern only if it can produce at a cost below the market's price. Nevertheless, the economic tools made available to technical decisionmakers are generally simpler than their physical model analogs. Interestingly, the same engineering approaches at work within physical models can be harnessed to shed light on techno-economic questions. This article describes methods, referred to collectively as process based cost modeling, which attempt to do that. Just as the former set of models has been developed to avoid undue experimentation, cost models, have been developed to avoid expensive strategic errors in product development and deployment.

WHY APPLY ENGINEERING PRINCIPLES IN THE ANALYSIS OF COST?

On the face of it, cost appears to be a simple metric -- the financial consequences of an action. It is a concept which we deal with daily and with which we are generally comfortable in both personal and professional contexts. However, in the context of relating specific technical changes to their economic implications, cost can become a more elusive measure. The classical tools for analyzing costs are based soundly in an accounting heritage which focuses upon the performance of existing facilities and designs. This historical and aggregate focus places definite limits on the scope and relevance of the resulting analyses. To put it plainly, regardless how well an accounting system describes the cost of operating a particular process, that information cannot be used alone to understand how those costs will vary in response to changes in part design, material, or operating conditions, not to mention, wholesale process technology change. As an example, consider substituting materials within an existing process. Will costs change only by the difference in new and old material price? No, with the new material will come distinct yields, operating rates, tooling life, etc. Ultimately, the difference is more than merely the material employed; the characteristics of the process employed must also be taken into account.

MODELING FEATURES OF COST

Although process-based cost models (PBCMs) share the characteristics of other process models, there remain several considerations in their implementation which derive directly from attributes of cost. First of all, more than any purely physical measure, the cost of a product is entirely context dependent. This is a direct consequence of the interrelated nature of product design and production cost: While the cost of a product is a function of the process used to make it, at the same time, the cost of operating a process is a function of the design of the product being produced. As such, both modeler and analyst must be aware that all cost results are not intrinsic features of product or process, but are strongly tied to the execution and synthesis of the two.

The modeling of cost is further complicated because it is difficult, if not impossible, to bound exhaustively the economic consequences associated with any complex undertaking. Table 1 gives a flavor of the varied costs which can play a role in creating any generic product. This list is not exhaustive and many of its elements could be subdivided further. Nevertheless, it hints at the challenge of getting a hold of all cost implications. An additional concern which arises from the "laundry list" of costs in Table 1 is how to correlate some cost elements, for example marketing costs, with process and product characteristics, ostensibly the goal of a modeling effort. In fact, satisfactory methods often do not exist. Fortunately, when answering questions involving comparison, it is generally not necessary to account for all of these for a particular product. Specifically, those elements of cost which are independent, or nearly so, of technology choices frequently may be omitted from a comparative analysis. Implicitly, therefore, the cost elements necessary for comparing alternatives can vary significantly, depending on the question being answered. As such, any procrustean definition of relevant elements of cost is inappropriate, leading either to omission or unnecessary effort. Instead, a process-based cost model must be built with the answering of a particular question in mind. Only given the context of the question can the appropriate scope and depth be determined.

Possible Cost Elements	
Material	Installation Expense
Energy	Tools, Molds, Dies
Labor	Building Space
Primary Equipment	Overhead Labor
Auxiliary Equipment	Transportation
Waste Disposal	Marketing
Advertising	Packaging
Insurance	Taxes
Warehousing	

Table 1. Elements of Manufacturing Cost

MODELING CONCEPTS

A process-based cost model, like any other engineering process model, serves as a mathematical transformation, mapping a description of a process and its operating conditions to measures of process performance, in this case cost. Unfortunately, the measures of performance which are of most interest are rarely determined directly by those operating conditions that are most convenient to measure or to manipulate. Therefore this transformation must be built up in a stepwise fashion repeating the following two tasks:

1. Isolating those factors which directly determine the metric being estimated and then
2. Understanding how the magnitudes of those factors are set by the process in question.

As an example, consider the creation of a process model which will predict the strength of a piece of steel following a heat treatment procedure. To make a successful prediction, first, the relevant underlying mechanism which effects strength must be established. For the purpose of discussion, let us define the determining factor to be the size of grains within the steel. Since grain size is not a directly controllable process parameter, it is necessary to understand how this factor is influenced by process operating conditions. Further simplifying, let's assume that solidification rate solely determines grain size. However, again, solidification rate is not a parameter which can be set directly, so the model is not yet complete. Continuing this process we could build up a causal chain such as material and ambient temperatures combined with material properties set the parts cooling rate, which, in turn, determines part temperature and thus the solidification rate, which sets the grain size and therefore the strength. While this simplifies a complex process, it serves to illustrate the manner of creating a process model, working backward from the desired measure of performance (strength) through intermediate determining factors (grain size, temperature, etc.), until reaching a set of measures which are controllable by the model user (process temperature). Interestingly, therefore, while the a model works forward connecting initial conditions to outputs, the modeler works backward finding connections between the outputs and the initial conditions which influence them.

The process-based method derives cost from the magnitude of directly contributing factors -- e.g., operating time, quantity of raw material -- which are themselves built up from the effects of manipulable process parameters -- e.g., operating temperature, part dimensions. Building a robust model potentially requires connecting a lengthy chain of consequences between production cost and a set of controllable design and operational parameters.

PROCESS-BASED COST MODELING

A process-based cost model is constructed using this very approach, working backward from cost to technical parameters which can be manipulated. For modeling costs, this involves three steps:

1. Identify relevant cost elements
2. Establish contributing factors
3. Correlate process operations to cost of factor use.

The following paragraphs describe the general implementation of these. These methods were first described by Busch[2] and Busch and Field[3] and have since been applied to a number of specific processes.[4][5][6][7][8][9][10][11][12] The interested reader is referred to these references for further reading.

1. Identify Relevant Cost Elements

Technical changes impact many elements of product cost. At the same time, it is often impractical or inefficient to model each and every impact. Therefore, when addressing real world problems, it is left to the modeler to determine which set of cost elements -- labor, energy, equipment, maintenance, overhead, etc. -- will be considered. Because the set of relevant cost elements can vary from model to model and because a focus of PBCMs is to provide a clear framing of any debate about cost, it is critical that those costs considered be identified explicitly and listed clearly both for the modeler and for anyone examining model results.

The relevance of any particular cost element is a function of both the process under consideration and the question which the model is to address -- the goal of the analysis. PBCMs have been applied primarily to questions of technology choice for functionally equivalent products and have, therefore, focused on the cost elements shown in Table 2.[13] These individual elements reflect the line items of classical accounting methods providing consistency with conventional views of cost. Nevertheless, this list is not exhaustive or exclusive and it should be expected that specific situations may require examining other costs. For example, while transportation cost may not be a direct consequence of a plastics forming technology, it may be pertinent if one is comparing the cost of producing plastic parts versus analogous, but heavier metal parts. Similarly, while waste disposal is a minor consideration for many forming processes, it plays a significant role if investigating technologies with either hazardous or, on the other hand, valuable scrap. Finally, logistics costs may play a role in comparing processes which have different batch production characteristics.

While trivial, it is important that this first step not be overlooked. This is true foremost because it is often more difficult than expected to identify all of the repercussions of a design, material, or process change. However, even for those cases where the modeler is comfortable with the set of economic consequences being considered, the nonstandard definition of cost, or at least of cost's scope, demands a clear list of what costs a model considers. This list is a necessary characteristic of a credible and maintainable model.

Common Cost Elements	
Material (incl. scrap)	Installation Expense
Energy	Tools, Molds, Dies
Labor	Building Space
Primary Equipment	Overhead Labor
Auxiliary Equipment	Transportation

Table 2. Elements of Manufacturing Cost Commonly Considered in Some PBCMs

2. CATALOG CONTRIBUTING FACTORS

The previous step can be thought of as defining the modeling problem, particularly, the model's scope. With that definition in hand, it is possible to proceed to mapping the details of the manufacturing process. The first detail is to establish the specific production factors -- materials, labor, capital equipment, and energy -- which must be purchased or allocated to manufacture.

In compiling this catalog, each factor must be described in sufficient detail to fully assess its cost. For example, in modeling sheet forming operations one needs to know the type and potential producible force of the presses which will be used. These specifications are necessary to establish the press's price. In some cases, this part of the model may simply be a list of the resources used in production, each with a constant entry describing its characteristics or at minimum the cost of allocating that factor. However, a simple list should never be viewed as satisfactory. In fact, since an important role of PBCM is to inform decisions about technologies which may not be currently in operation, it is imperative that, whenever possible, models be able to forecast the implications of technical variations. A pertinent example found in robust models is the prediction of equipment specifications sufficient to produce the product of interest, essentially, a minimum equipment size. The specifics of a model of plastic injection molding show this well. When injection molding, physical laws dictate that the clamping force required to hold the dies closed must be greater than the force generated normal to the plane of die separation. This force can in turn be directly related to the filling pressure and to the cross section in that plane of the part being produced. With enough information and computational expense, the relationship between these design parameters and the required clamping force could be modeled with painstaking accuracy. However, an informative prediction can be found from a rougher description of part specifications through a regression of data on existing molded parts. In a study by Busch [2] , this approach yielded a definition of press clamping force as:

$$ClampForce = SectionArea\left(\frac{224}{\sqrt{MaxWallThickness}}\right) + 172kN$$

where *SectionArea* is the projected area of the part in the die separating plane and *MaxWallThickness* is the greatest wall thickness within that part. As described later, this clamping force serves as a size parameter from which to determine the cost of the injection molding equipment. It is worth noting what is captured and not captured by this relationship. As stated above, clamping force would be expected to vary with part geometry and the force at which the polymer is injected. However, the relationship as stated does contain pressure as an explanatory variable. Likely, this results from examining a set of polymers which are injected at roughly the same pressure, making its effect consistent and not resolvable. This is a good example of models being strong at answering those questions for which they were designed, but always suspect as one deviates from that context. Specifically, if one was interested in a polymer which is processed at pressures much different than those investigated, this model may not accurately forecast the equipment required. Model users should be aware that limits on time and resources will ensure that engineering approximations like this will be used. In response, therefore, model users must always understand the context for which a model was built and how their question may differ from that.

It is clearly not necessary to forecasts the characteristics of every factor employed in production. (e.g. For most processes, the type of labor will be the same regardless of the part which is being produced or the specific operating conditions which are chosen.) Nevertheless, for those factors which may change, incorporating a relationship which forecasts their characteristics makes a model much more powerful in its ability to investigate previously untried operational scenarios.

3. CORRELATE PROCESS OPERATIONS TO COST OF FACTOR USE.

The third step in creating a process-based cost model is translating the list of input factors into actual costs. From an abstract perspective, this calculation can be further broken down into two parts: 1) determine what quantity of the factor is required and 2) determine the price attached to the use of each unit of that factor. The resulting factor cost is simply the product of the quantity and unit price. Element costs are defined as the sum of all of the individual factor costs which fall under their heading.

The cornerstone of a useful cost model is forecasting the required quantity of each factor input. Every factor can be used to produce only a fixed and finite amount of goods. Producing beyond this limit is not feasible without additional factor units. Capturing this relationship between consumption of factor inputs and production of process outputs is fundamental.

Before preceding to specific modeling strategies, it is helpful to point out that cost elements have historically been grouped into two categories -- variable and fixed. Variable costs are those that can be directly associated with the production of a unit of output, and whose magnitude (on a per period basis) increases roughly linearly with the total number of units produced. For example, material costs are variable costs, since a doubling of the total number of parts produced requires a doubling (or near doubling) of the amount of material that will be consumed. Variable costs are contrasted with fixed costs, which do not increase linearly with total production. The prototypical fixed cost is expenditures for capital equipment. When considering varying levels of process throughput, the amount of equipment, and its associated cost, remains constant with increasing output until its production capacity is exceeded, whereupon more equipment is required. The perverse consequence of these definitions is that, when considering costs on a per piece basis, the variable costs remain constant as the production volume changes, while the fixed costs change. Conversely, when considering total costs to produce a specific number of parts, then the variable costs vary with that number, while the fixed cost remain fixed for small changes in production volume.

While it is not possible to describe a best modeling strategy for all cases, one which has proven to be successful is to compute factor cost on the basis of one fiscal period (generally one year). Strategies for implementing this for key cost elements are summarized below.

VARIABLE COSTS

MATERIAL COST

The cost of material can be estimated as a function of the price of the raw material, the design of the component and the yield associated with the process. Essentially, the problem is one of determining the total amount of material actually required by each part, realizing that there will be material losses as a result of both intrinsic features of the process and quality control measures. Intrinsic process losses include trim scrap as well as material required to deliver a charge into a mold (e.g. the frozen contents of runners and sprues). Therefore, annual material requirement is the gross material per part (including scrap losses) times the gross production volume. (See the later section on intensity of production for a definition of gross production volume.) Each of the involved parameters, mass, scrappage and yield can either be a direct input to the model or a more complex function involving other engineering parameters.

One common mistake in assessing material costs is to neglect the value of process waste streams. Although waste disposal costs certainly can be accounted for separately, their rough correlation with material inflows makes material cost the natural heading under which to aggregate them. An oft overlooked type of waste "cost" is revenue from salable scrap, an asset commonly found in metals processing. Note that scrap materials, although potentially a valuable source of revenue, generally sell for much below the cost of input raw materials.

DIRECT LABOR

Direct labor costs are a function of the wages paid (including all costs to the manufacturer of employing a worker), the number of laborers necessary to run the process and the paid operating time. Typically, only direct laborers are included in this calculation, with the remainder accounted for in the overhead calculation (see below). The crucial part of this calculation is determining the paid operating time. When looking at this from a part perspective it is tempting to simply use the cycle-time for creating the part, however, this must be corrected for labor productivity. To do so, it is often simplest to compute the annual paid operating time, allocate an appropriate portion to the product of interest, and then compute a unit cost by dividing by the net annual production volume.

ENERGY COST

For many operations, energy consumption can be calculated from the theoretical energy requirements of processing the part. For those where energy expenditures are significant , this should be carried out with the same kind of rigor described previously concerning press size or subsequently concerning cycle time. Regardless of the underlying analytical rigor, this calculation should be augmented in the model with a permutable correction factor to account for real world inefficiencies. For other less energy intensive processes, regression analysis of energy consumption is generally sufficient. Unfortunately, statistical analysis of in-practice energy use is often hindered, because direct metering of energy consumption by individual equipment is rarely done. Instead, as a proxy, rates can be estimated from the listed consumption requirements of the processing equipment. A useful approach is to build a regression of rate of energy consumption versus the equipment size parameters mentioned in the previous section. Energy costs then become a product of this rate, the prevailing energy price, and the operating time required to produce the part. For this calculation, it is appropriate to use the gross operating time, thereby accounting for energy expended on rejected parts.

FIXED COSTS

Fixed costs generally fall into one of two groups, those which are one time capital expenses and those which represent recurring payments only weakly related to the quantity of parts produced. Recurring payments, like building rent, are easily annualized or converted to any pertinent time period basis, but one time payments require some scheme to allocate their costs over the duration of production. Given that capital goods can remain productive for years, or even decades, it is important to factor in the time value of money into this allocation. It might be tempting to do this only if the funds for purchasing the capital come in the form of a loan, but remember that moneys used to purchase capital could have been put to some other use. As such, the true cost of capital must include foregone income regardless of the source of funds. Financial texts explain this in detail, but here it will suffice to say that one can annualize a one time expenditure as well as capture its associated opportunity cost by multiplying it by the capital recovery factor:

$$CRF = \frac{[r(1+r)^m]}{[(1+r)^m - 1]}$$

In this relationship, *m* is the number of periods over which the cost is allocated and *r* is the percent discount rate representing the time value of tying up assets in this capital. For this equation, the relevant number of periods, *m*, may be different for each of the elements of cost, even for the same process. For example, tool dies or molds, which can produce only one type of part, should be allocated fully over only the years when that part is made. In contrast, a building can serve to host the production of many generations of parts and, therefore, should be allocated over a longer, multi-decade period. Lying in the middle of these extremes is the allocation period of production equipment. Generally, equipment which can accept tools can be used for at least a few generations of products and so should likely be allocated over an appropriately matched period. Ultimately, it is important to realize that there is an arbitrary nature in picking an allocation period for any not fully dedicated capital. As such the method of allocation and the driving parameters should be stated clearly and be easily permuted in any PBCM.

EQUIPMENT COSTS

In the preceding section, it was mentioned that models should, whenever possible, include relationships between the process parameters (the design of the part, the material of which it is made, and how the process is operated) and some set of minimum-size parameters for the manufacturing equipment. To convert this to cost, the model should also include statistical data relating those size parameters to the price for that equipment. Since equipment purchase is a type of one-time expense, this cost should be annualized over a number of years equal to the productive life of the equipment. As just mentioned, this productive life is usually longer than the number of years over which an individual product is made.

While it is useful for models to incorporate information about equipment prices, it is critical that they include the ability to compute how many pieces of equipment, working in parallel, are required to produce a specified number of parts in the required time period. To compute this, divide the desired annual throughput (i.e. gross throughput) for each process step by the maximum throughput which an individual piece of equipment, or line, can handle in one year. The latter quantity is not an intrinsic feature of the equipment and so should be further deconstructed within the model. Specifically, the maximum annual throughput for one line is the available operating time for that line divided by the cycle time for the part being produced. Together these yield:

$$\#\,of\,Parallel\,Lines = \frac{(Total\,Parts\,Demanded)}{(Max.\,Parts\,per\,Machine)} = \frac{N^*}{\frac{(Available\,Time)}{(Cycle\,Time)}}$$

where N* is the gross annual production volume. Therefore, if a particular product/process combination has a cycle time of 9 minutes and is operating in a plant with 1,500 productive operating hours per year (90,000 minutes), the equipment would have a maximum throughput of 10,000 parts per line. Furthermore, creating a plant with a capacity of 75,000 parts per year would require 7.5 lines -- Or would it be eight? The following paragraph describes how to answer this last question.

Although in real life one can only possess integral numbers of production lines, the calculation just described can yield fractional results. Depending on the situation being analyzed there are two ways to handle this. If one expects that the production lines will be dedicated to the product under consideration (i.e. only used to produce *that* product), then the above result must be rounded to the next higher integer -- even if 2.5 lines will do, three must be purchased. However, parts are often manufactured on equipment which is shared by numerous other parts. In these cases, the equipment is not dedicated to one product, so each product should be allocated a cost based on the fraction of time which it ties up the machine -- generally a non-integer fraction. The above formula can be used as is for these situations.

In some cases, it is appropriate to assume that a given level of investment in the primary equipment for a process requires a corresponding fixed level of investment in auxiliary equipment. Consequently, in the absence of detailed production facility information (usually resulting from insufficient time to collect it), auxiliary equipment costs can be estimated as a fixed percent of the main machine cost. Regarding this point, the modeler must always be wary of whether price quotes include complete turnkey operations (i.e. which would include all requisite auxiliary equipment) or only the primary equipment.

TOOLING COST

Tooling cost is possibly the most difficult component of cost to estimate. This is true largely because each set of tools is unique, reflecting design choices and available production equipment. This uniqueness also arises from the fact that tools are often handmade, requiring considerable craft and special skills that are not widely available. A reasonable approach to estimate the price attached to each set of tools is using empirical data to relate prices paid for previous tools to parameters describing the components they produced. While such estimates (usually regression models) are imperfect, they can yield good first order approximations. In annualizing tooling costs, remember that they are always dedicated costs and must be fully allocated over the number of years which the product will be produced.

BUILDING

Building costs are relatively easy to calculate. Prices per square meter of building space are readily available, and the space requirement can be related to the equipment size parameters and conventional practices (e.g., materials handling requirements, safety specifications, etc.).

OVERHEAD

The cost of operational overhead, including all those resources not directly involved in manufacture, is a figure which can be difficult to relate to features of a process, but which can represent a significant expenditure. One approach is to estimate this cost using a burden rate which is applied against the magnitude of the other fixed costs. The underlying idea here is that a given level of fixed cost investment requires a fixed amount of supervision and other support staffing as well as the facilities to support those employed in production. Such a simplistic treatment of overhead is usually acceptable when the goal is to analyze the relative costs of technical changes in part or process.

IMPORTANT CONSIDERATIONS

As described previously, production cost is built up from intermediate process variables. Two groups of variables which influence almost every cost element are those relating to 1) the intensity of production (i.e., the number of units produced) and 2) the operating time, in its numerous forms. Carefully considering these can make the overall modeling task much more straightforward and will lead to a more robust model.

INTENSITY OF PRODUCTION

Ultimately, the cost of production is a function of the number of units produced. Even fixed costs depend on the total throughput demanded of a facility. Because of this role, production volumes must be carefully and clearly accounted for within the model. In doing so, two aspects of production volume must be kept distinct. These are 1) the demanded output of the facility -- the net production volume (PV) -- and 2) the total number of units which must be produced to generate that output -- gross production volume (GPV). The latter differs from the former by including parts produced but subsequently rejected. In general, the total cost per period (for all cost elements) is a function of the gross production volume, while the unit cost is derived from the total period figure by dividing by the net production volume. The net production volume should be a scenario input parameter which can be easily varied within a model.

In the real world, facilities must be constructed to meet a particular demand, but this demand may not occur, leaving the facilities underutilized. Therefore, it is often useful to build into a model an input for net facility capacity. This would necessarily be separate from the net production volume input. Net facility capacity can be used to derive a gross facility capacity (GFC) which is used in place of the GPV to determine the magnitude of total fixed cost expenditures. Normally, it would not be appropriate to use the GFC to compute total variable costs. Separating capacity from actual production volume, allows a model to be used to investigate how steeply costs will climb if an operation is not fully utilized.

TIME

As with production volume, operating time is fundamental to production cost. For modeling purposes, operating time must be looked at in at least three subtly different ways -- available operating time, paid operating time, and required productive operating time.

The first, available time, represents the time when work can be performed. This is computed directly from parameters describing how the plant is run, such that annual available time equals the productive working hours per day times the number of days per year which the facility is open. The productive working hours per day must not include 1) planned, unpaid downtime (e.g., plant is closed or workers are on unpaid breaks), 2) planned, paid downtime (e.g., paid worker breaks or process maintenance periods) or 3) unplanned downtime -- generally paid.

The second pertinent aspect of time, paid operating time is computed just like available time, but daily paid time should exclude 2 and 3 -- planned, paid and unplanned downtime. As the name indicates, annual paid time should be used to compute labor costs.

Finally, required productive operating time, represents the total amount of time needed to produce the gross number of pieces demanded. This figure is simply the GPV multiplied by the cycle time per part (modeling that cycle time can be quite involved and is discussed in detail subsequently). Looking back to the discussion of equipment costs, the number of parallel lines can be computed from the quotient of required productive time and available time. Regarding variable costs, the required productive time is the appropriate measure to use in computing energy costs.

CYCLE TIME

The time to produce a part, its cycle time, is determinant for many elements of manufactured part cost. For fixed costs, cycle time influences the number of parallel streams necessary to achieve a specified production volume. Similarly, variable costs, like labor and energy, are directly dependent on the time it takes to complete the production process. Given this level of impact, it could be said that understanding the relationship among part design, process operating conditions, and cycle time is the primary goal of any cost model. For some processes, the cycle time may be effected more prominently by properties of the part (e.g., the dimensions of an injection molded part), while in others it may depend more on process operation variables (e.g., operating temperature of a pyrolysis plant). Processes where cycle time is related poorly to both classes of parameters (e.g., the painting of a picture) may not be suited well to evaluation through process-based cost modeling.

In theory, there are two ways to estimate cycle time, theoretical and statistical. In practice, models combine both methods to achieve the best result. Perhaps, this is best shown using an example for which plastic injection molding will serve nicely.

The injection molding cycle can be broken into the seven stages shown in Figure 1[14]. This diagram highlights two approaches to computing cycle time -- 1) model each of the stages individually or 2) substitute the cooling time as a proxy for the middle stages. Regarding this problem, the latter is the better choice, both because it reduces the number of stages to examine and because cooling time is a quantity amenable to theoretical modeling.

Having settled on an overall strategy, the next question to address is how will these constituent times be modeled. One option is to create inputs in the model for each stage, forcing the user to enter the times. Given the importance of time to cost, this should never be a satisfactory solution, especially, because none of these times represent values which a designer or decision-maker should be expected to know for a part not yet in production. Instead, a more robust model incorporates relationships which forecast these times. To construct such relationships, consider how each time is related to the product's design or the process's implementation. While a thorough modeling breakdown for each process stage is beyond the scope of this article, two examples will be instructive. First, a simple example, the duration of mold opening and closing is likely related to the opening speed of the press and the distance that the mold must be separated. Furthermore, the latter could be proportional to the height of the part. Since press opening speed can be gathered from equipment literature and part height is an reasonably expected design input, this simple model can trace to an acceptable endpoint. Of course, actual practice may complicate this issue. Presses may always open to the same height, regardless of part, or the time required to remove part from mold may overwhelm other times. Nevertheless, the point here is to see how one can construct a model by simply reasoning through the characteristics of a process.

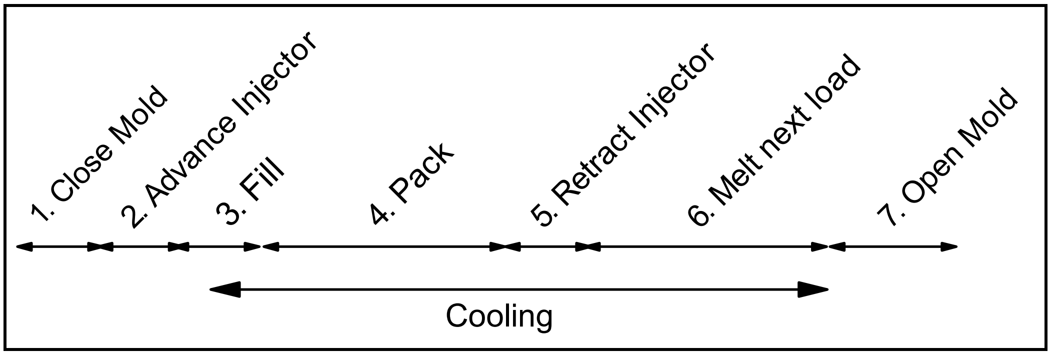

Figure 1. Plastic Injection Molding Cycle Time

While many aspects of cycle time can be approximated this simply, others should be treated with more rigor. With respect to injection molding, the cooling time provides such an opportunity. In fact, software packages are available which combine finite element and difference methods to accurately simulate flows, pressures and temperatures throughout the injection cycle. In doing so, these packages can forecast the cooling time with an accuracy more than adequate for cost estimation. However, this precision comes at the expense of required design and process detail (e.g. CAD drawings). For situations where those are unavailable, simpler models can still provide insight. As an example, Busch[2] assumed that injection molding cooling time would equal the time required to cool the thickest section of the part, which was approximated as the time to cool a semi-infinite plane of equivalent thickness. By using such a relationship, the model captures cost behavior related to design (e.g. wall thickness), material (e.g. thermal properties), and operating conditions (e.g. melt temperature).

Obviously, cycle time can be modeled throughout the range of sophistication. However, regardless how cerebral the model, any appreciation for the power of theoretical modeling must be tempered by a realization of its limits. Real world equipment always runs sub-optimally. Furthermore, even disregarding inefficiencies, actual cycle times include margins of safety to account for lot to lot and unit to unit variation, adding to further deviation from theoretical predictions. Therefore, to improve accuracy, theoretical models must be complemented with statistical analysis of time study data from existing operations whenever possible. The previously cited study by Busch gives an excellent example of this. The cooling time estimate described above is an acknowledged lower bound, underestimating time to cool for curved sections and ignoring inefficiencies in transferring heat from melt to mold. To accommodate this, the computed cooling time was augmented with regression analyses of data collected from production sites. Since cooling time is not a directly observed characteristic, this was carried out as part of a regression analysis of total cycle time versus the cooling time estimate as well as several other parameters. That analysis found cycle time to follow:

$$t_{cycle} = 1.35t_{cool} + 0.015w + 8.9 \text{ seconds}$$

where t_{cool} is the calculated cooling time in seconds and w is the part mass in grams. The coefficients were estimated using data from 33 manufacturing operations, representing parts weighing between 5 and 2780 grams. Note that elements of this equation follow logically from the stages of the injection molding cycle. Obviously, the first term captures the cooling part of the cycle. The second term likely accounts for those stages proportional to part dimensions, such as filling -- related to part volume -- and mold open/close -- related to part height. Finally, the constant term captures those parts of the cycle which are little effected by technical change, like injector advance. While regression estimates are not always precise, in this case, the cycle time equation explains 90 percent of the variation in the data, and each independent variable was statistically significant with a 99 percent level of confidence.

It is often tempting to create a PBCM using only statistical methods. However, while statistical models can be quite accurate, they are based on data covering a finite range of conditions. It is impossible to know whether the trends over that range continue for cases beyond. Theoretical models can help deal with this shortcoming. While a theoretical model may not always be accurate, if properly constructed, it may be able to reveal the general shape of cost behavior over a broad range of conditions. As such, combining these two can provide both scope and accuracy in a model. Of course, there will always be cases where a model is incorrect. However, the goal of the process-based cost model is to allow decisions to be made based on *all* of the available information, conceptual and empirical.

MATERIAL FLOWS

The tracking of material flows is one aspect of modeling cost which can be quite simple, but which is often neglected. Material flows are important in that they determine both the intensity of production at each process step and the magnitude of material and waste costs. Inaccuracy arises when a modeler fails to recognize that the magnitude of flows change from one step to the next, modified by the losses at each step in the chain. For most production processes, it is of most interest to see how costs respond to changes in net output from the final step. Fixing the magnitude of that output and assuming that each step operates to satisfy the demand of the next, the intensity of production of each step is established by its own yield and the production volume of those steps subsequent to it.

The best way to handle this issue within a model is to break down the overall process into its individual steps, explicitly tracking material flows for each. By tracking material flows separately, it becomes convenient to assign distinct material and scrap costs throughout. Also, these material flows define the production volume for each process step. Maintaining discrete production volumes serves to remind that capital requirements for each step must be assessed separately. Finally, it is generally best to report the material flows for all steps in one common unit and in one common place within the model. (They can reported as needed elsewhere.) This approach facilitates reality and error checking.

CONCLUSION

None would deny the driving role of cost in all technical decisions. Conspicuously, however, of the tools made available to technical decisions makers those assessing cost are often far less sophisticated than their physical model analogs. Process-based cost modeling has emerged to address this discrepancy. In particular, PBCMs are built around the idea that cost derives from the synthesis of part design, material properties, and operating conditions all molded by the physical realities of a specific process technology. Within this context, PBCMs attempt to leverage all available information, technical and strategic, in the decision process.

To put these concepts into practice, the modeler must first and foremost define the question he or she is trying to answer. Having that in place, the work can proceed through three stages:

1. Identify relevant cost elements
2. Establish the set of contributing factors
3. Correlate process operations to cost of factor use.

In executing the third step, the modeler must pay particular attention to 1) intensity of production, resolving the concepts of capacity and production volume and accounting for losses throughout the system; 2) operating time, including available, paid, and required productive operating time with careful attention given to process cycle time; and, finally, 3) material flows, recognizing that they can vary throughout a multi-step process.

When implementing a PBCM, a primary consideration must be transparency. Cost, always a nebulous concept, means different things to different people with definition, context, scope, and accounting practice driving this divergence. As such, economic decisions can be hampered when comparing dissimilar computational methodologies. However, PBCMs attempt to combat this by breaking down cost logically and thoroughly. In doing so, properly constructed models allow the debate to move swiftly through any discussion of methodology and, therefore, to focus on the strategic variables and choices. To accomplish this, the onus falls to the modeler to explicitly defined those elements of cost which are considered within a model. Furthermore, those aspects of a model which are purely strategic, such as production scale or discount rate, must be clearly stated and easily permutable.

Past experience with cost modeling has shown that fair estimates can be built up from limited design and operational data. This is true because engineering models and statistical information can be combined to relate that data to cost through determining factors such as cycle time, material consumption, and capital requirements. Ultimately, by making this stepwise transition, process-based cost models allow the decisionmaker to make choices early in the design process, avoiding expensive strategic errors in product development and deployment.

[1]Ashby, M.F.; "Physical modeling of materials problems", *Materials Science and Technology*, Vol. 8, February 1992, pp. 102-111.

[2]Busch, John Victor; *Technical Cost Modeling of Plastics Fabrication Processes*, Ph.D. Thesis, Massachusetts Institute of Technology, May 1987.

[3]Busch, J. V. and F. R. Field, III; "Technical Cost Modeling;" Chapter 24 of the *Blow Molding Handbook*, Donald Rosato and Dominick Rosato, eds.; Hanser Publishers, New York, 1988.

[4]Poggiali, Barbara; "Production Cost Modeling: A Spreadsheet Methodology;" S.M. thesis; Department of Materials Science & Engineering; Massachusetts Institute of Technology; Cambridge, MA; Aug. 1985.

[5]Ng, Lee Hong and Frank R. Field, III; "Materials for Printed Circuit Boards: Past Usage and Future Prospects;" *Materials and Society*, Vol. 13, No 3; 1989.

[6]Arnold, Scot, Nicolas Hendrichs, Frank R. Field, III, and Joel P. Clark;" Competition Between Polymeric Materials and Steel in Car Body Applications;" *Materials and Society*, Vol. 13, No 3; 1989.

[7]Nallicheri, Narayan V.; *A Technical and Economic Analysis of Alternate Net Shape Processes in Metals Fabrication*, MIT Ph.D. Thesis, June 1990.

[8]Han, Helen N.; *The Competitive Position of Alternative Automotive Materials*, MIT Ph.D. Thesis, May 1994.

[9]Politis, Dimitrios; *An Economic and Environmental Evaluation of Aluminum Designs for Automotive Structures*, MIT S.M. Thesis, May 1995.

[10]Chen, Andrew Chinshun; *Economic Aspects of Materials Substitution in Horizontal Automotive Body Panels: The Issue of SMC Surface Finish*, S.M. Thesis, Massachusetts Institute of Technology, May 1992.

[11]Kang, Paul A.; *A Technical and Economic Analysis of Structural Composite Use in Automotive Body-In-White Applications,* S.M. Thesis, Massachusetts Institute of Technology, May 1998.

[12]German, Luis; *Low Volume Manufacturing Strategies for the Automotive Industry: A Global and Emerging Economy Perspective*, Ph.D. Thesis, Massachusetts Institute of Technology, May 1998.

[13]Clark, Joel P., Richard Roth, and Frank R. Field III; “Techno-economic Issues in Materials Selection”, *ASM Handbook Volume 20: Materials Selection and Design,*

[14]G. Potsch and W. Michaeli, *Injection Molding: An Introduction*, Hanser Publishers, Munich, 1995.