Chapter 2. Process-Based Cost Models

Introduction

The field of process engineering is rife with methods and approaches to modeling. Model in this context refers to a mathematical transformation from some description of initial conditions to the resultant set of final characteristics. Given this definition it is clear that even a simple equation which is familiar to any technical person, like $a = \frac{F}{m}$, is in fact a model of the way the physical world behaves. Within this example, the knowable initial conditions are the mass, *m*, and applied force, *F*. These map directly to the modeled final characteristic, acceleration, *a*. In the main, models for process engineering focus upon either prediction of the physical characteristics of products as a function of processing conditions or prediction of the necessary processing conditions to achieve desired product characteristics. In either case, the objective is to fine-tune processing parameters efficiently through analytical methods rather than through repetitive, time-consuming, and potentially expensive process tests and experiments. In addition to models that focus on the physical consequences of process variations, there are those that map the economic consequences of these same variations. Just as the former set of models has been developed to avoid experimentation through the analytical application of engineering and scientific knowledge, cost models, using many of the same principles, have been developed to avoid expensive strategic errors in product and process development and deployment.

The analysis of processing cost is a long-standing method for evaluating the relative merits of process and material alternatives, as well as a mechanism for identifying key processing parameters and opportunities for process improvements. However, the classical tools for these analyses are based soundly in an accounting heritage which focuses upon the performance of existing facilities and designs. This historical focus places definite limits on the scope and relevance of the resulting analyses. No matter how well an accounting system describes the cost of making a die-cast zinc part, that data cannot be used as a basis for estimating the cost of making a competing injection molded nylon part. The differences are greater than merely the material employed; the characteristics of the process employed must also be taken into account. The integration of elements of these classical economic methods with engineering process models has proven to yield a flexible and powerful tool for cost estimation and analysis. With such an integrated tool, it is possible to evaluate not only existing processes and designs, but also to assess the economic opportunities presented by processes and products that are still under development.

Additionally, process engineering approaches to cost can form a basis for discussion about cost even when the participants come from different cost accounting backgrounds. While classical accounting-driven models of cost are effective bases for management tools within an organization, they can be impediments to discussions across organizations, due to the large number of unspoken assumptions which necessarily underlie any real management accounting system. In contrast, a process-based model of cost frames the discussion with the engineering elements of the model. This, in turn, makes it easy to identify assumptions and conditions which influence the cost estimates under consideration.

Modeling Features of Cost

While process-based cost models share the characteristics of other process models, there remain several considerations in their implementation which derive directly from attributes of cost. Firstly, more than any purely physical measure, the cost of a product is entirely context dependent. Some physical properties do share this characteristic to a limited extent. This can be seen in the yield strength of steel which can vary seven to ten fold depending upon processing conditions. [ASM 97] However, the relevant context for determining cost encompasses a much wider array of specifications. In fact, these include not only process specifications, but also the time and place in which the process is executed. Furthermore, the modeling of cost is complicated because it is difficult, if not impossible, to define exhaustively the economic consequences associated with any remotely complex undertaking. It is important to underline that this lack of definition does not stem simply from ambiguous nomenclature, as is wholly to blame when "strength" is carelessly applied to either yield strength or ultimate tensile strength. Instead, the trouble arises from the many elements of costs which arise from any manufacturing activity. Table 2.1 gives a flavor of the varied costs engendered in realizing any generic product. This list is not exhaustive and many of its elements could be subdivided further. Ultimately, this

Common 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 2.1. Elements of Manufacturing Cost

ensures that it is difficult to enumerate all of the economic consequences of a particular manufacturing activity, especially since those consequences may differ for varied companies, locations, and contexts. As a result, the modeling of costs requires that the output of the model be defined explicitly. In turn, therefore, cost is not generally useful as an absolute description of manufacture. Instead cost, and hence a cost model, is a metric for making comparisons, evaluations, and decisions. It is for such a purpose that process-based cost modeling was developed and has been applied widely.

One concern which arises from the "laundry list" of costs in Table 2.1 is how to estimate or correlate some cost elements, like marketing costs, with process features and operating conditions. Fortunately, when answering questions of comparison, it is generally not necessary to account for all of these for a given product. Specifically, those elements of cost which are independent of material / process technology frequently may be omitted from the analysis. This is acceptable because of the purely additive nature of the cost, which permits the transitive comparison of costs minus those elements which are equivalent in both. The cost elements relevant to making a comparison can vary significantly, depending on the question being answered. For example, while the transportation costs associated with steel and ceramic engine valves is equivalent and, therefore, able to be omitted, the costs attached to trucking glass versus plastic beverage containers is significantly different and, hence, pertinent. Thus any Procrustean definition of relevant elements of cost is inappropriate. Instead, a process-based cost model must be built with answering a particular question in mind. Only given the context of the question can the appropriate scope and depth be determined.

Finally, when developing such models it is helpful to realize that, while rarely recognized as such, in all contexts the quantity being calculated (i.e. cost) is a rate. Generally, this rate is measured on a basis of per unit, C^u (e.g. per part or per ton) or per time period, C^t (e.g. per year). Fortunately, these two rates are related in an important and convenient way through the total quantity produced in a given time period, N, such that $C^t = NC^u$. For many calculations the most important period is a year in which case N is referred to as the annual production volume of a process. This relationship is useful because it allows cost to be calculated in whatever is the most convenient basis and then be readily and accurately translated into the other. Furthermore, any element of cost, like material, labor, or energy cost, measured on the same basis can be combined additively such that $C^x = \sum c^x$, where C^x is the total modeled cost measured in basis x, and c^x represents each of the cost elements also measured in basis x.

Technical Cost Modeling Primer

A particular type of process-based cost modeling, known as Technical Cost Modeling (TCM), was developed at the Materials Systems Laboratory at the Massachusetts Institute of Technology. TCM of manufacturing processes has been discussed by Busch [Busch 87] and Field and Busch [Busch and Field 89], but its key elements are summarized here.

As mentioned above, the TCM approach to process-based cost modeling, like any other engineering process model, serves as a mathematical transformation, mapping from a coordinate space which describes the operating conditions of a process to one which measures the performance of that process. Unfortunately, the measures of performance which are of most interest are determined directly in rare instances by those operating conditions that are most convenient to measure. Therefore, conceptually, creating such a transformation must be broken down into two tasks. These are 1) isolating those factors which directly determine the metric being estimated and then 2) understanding how the process in question determines the magnitudes of those factors. 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 taken into account. For the purpose of discussion, let us define the most relevant determining factor to be the size of grains within the steel. Knowing this, it is then necessary to understand how this factor is influenced by process operating conditions. Many studies have shown that material and ambient temperature determine cooling rate, which, in turn, determines solidification rates which then establishes grain size. While this simplifies a complex process, it serves to illustrate the manner of creating a process model. Again, as with all other process models, it is assumed that these determining factors are universal for a given parameter to all materials within a class and with some generalization to all materials. In these terms, the technical cost method estimates the contribution of process parameters to each of those factors which determine manufacturing cost. Like other process-based cost approaches, TCM grounds these estimates in engineering principles and in the physics of manufacture. At this point it is worth noting that not all performance metrics, cost or otherwise, can be related to a measurable operating condition through only one, or even a few, intermediary process characteristics. Instead, a rather lengthy chain of consequences, and the relationships between each, may be necessary to build a truly useful model.

Practical TCM

The steps necessary to create such a mathematical transformation for predicting cost can be described in a more practical sense as:

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

The following paragraphs detail the implementation of these.

The first of these steps, the identification of relevant cost elements, was informally discussed in the previous section. Due to its critical importance in creating a useful model, it warrants further discussion. This identification process always should be directed strongly by the question or

Prevalent TCM Cost Elements	
Material	Installation Expense
Energy	Tools, Molds, Dies
Labor	Building Space
Equipment	Overhead Labor

Table 2.2. Most Common Cost Elements in a Technical Cost Model

questions to be addressed by the model being created. In fact, the question being addressed impacts the development of a cost model so thoroughly that the explicit exposition of this question should probably be drawn out as a separate step zero in the above sequence. TCMs, in investigating questions of technology choice for functionally equivalent products, have traditionally focused on the cost elements shown in Table 2.2; all of which are closely tied to the characteristics of a process and its operations. In addition, for some questions comparing the economic consequences of discrete products, it may be pertinent to investigate derivative costs as well. An important example of this is transportation costs, which can be significant for some problems. Finally, since an important focus of TCM is to provide a clear framing of any debate about cost, it is important that those costs considered be enumerated clearly both to the modeler and to anyone examining its results.

The previous step can be thought of as defining the modeling problem. With a fully defined problem, it is then possible to proceed to the mathematical mapping of the manufacturing process. The first task is to identify those factors for which monetary factors must be expended in order to create the product of interest. Here, the term factor is borrowed from the nomenclature of economic production functions, a discipline which provides one of the roots of technical cost modeling. As such, a factor is not limited to only raw materials. Instead, it also includes labor and capital equipment, as well as any other product or service which must be purchased and allocated to realize a manufactured good. In some instances, this list of factors may simply be a catalogue of those resources which must be combined or used in production. A good example of this comes from a model of automobile shredding. At an average facility, the laborers employed include four in the shredding crew, three in ferrous separation crew, three in the maintenance crew, and two staff supervisors. This information, which completely defines the labor factor requirement, simply enters model calculations as constants. However, this step should not be viewed as simple list building for all of the factors involved. In fact, since an important role of TCM 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 design variations. A critical aspect of this forecast is the prediction of the appropriate technical factors which are to be used. An example of this in many models is the prediction of equipment specifications which are necessary to produce a product of interest. The specifics of a model of plastic injection molding show this well. When injection molding, physical laws dictate that clamping force required to hold the dies closed must be greater than the force generated normal to the plane of die separation during the mold filling. 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. This approach yields a definition of press clamping force as [Busch 87]:

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

Incorporating this type of relationship makes a model much more powerful in its ability to investigate process operating conditions which previously have been untried, by being able to forecast the exact type of factor used directly from relevant design variables.

The third, and final, step in creating a technical cost model is translating the list of input factors into actual costs. Although for some factors this calculation may be trivial, for others is it helpful to break it into two parts. These are 1) determine how much of the factor is required and 2) determine the price attached to the use of that factor. Both the factor quantity and its cost of allocation must be calculated relative to the basis of the cost element being determined. As mentioned previously, the cost basis should be chosen to facilitate this calculation. In mathematical terms, each element cost is the sum of the usage cost for each factor which is being assessed to that element. The factor usage costs are computed as the product of the required factor quantity and the factor allocation price. This can be represented in a general sense as:

$$c_i^x = \sum_j \left[Q_{ij}^x(\overline{X}) \times A_j^x(\overline{X}) \right] = \sum_j \left[Q_{ij}^x(\overline{M}, \overline{P}, \overline{O}, \overline{E}) \times A_j^x(\overline{M}, \overline{P}, \overline{O}, \overline{E}) \right]$$

In this equation, c_i^x represents the *i*th cost element, *Q* the factor quantity and *A* the factor allocation price. Both *Q* and *A* must be assessed for the same basis as c_i^x. The sum in this formula is carried out for all of the factors, *j*, which contribute to this cost element, *i*. As denoted by the double subscript *ij*, *Q* must be evaluated specifically for the cost element under consideration, while *A* is assumed to be specific only to a particular factor. Therefore, while often similar for some cost elements, the form of *Q* is determined both by the process technology being modeled and the specific factor *j*, while *A* is only influenced by the type of factor being allocated. Finally, TCM assumes that both *Q* and *A* potentially depend on $\overline{X}$, the set of variables which determine how a process is operated. For clarity, $\overline{X}$ can be broken into the vectors $\overline{M}$, the properties of the material being operated on, $\overline{P}$ the description of part being made, $\overline{O}$ the modifiable operational variables (e.g. temperature, running rate, etc.) and $\overline{E}$ the prevailing, exogenous economic conditions. Some of these subcomponents may be irrelevant and null for some processes.

Like determining factor type, the calculations of *Q* and *A* can range in complexity from constants to formulae, which are dependent on process operating conditions. As an example, when calculating the cost of material in a injection molded part, the quantity of the factor allocated is described as, *Q = Part Weight*, and the allocation cost is simply, *A = Material Price per Unit Weight*. Combined this gives $c^u_{Material}$ *= (Part Weight) x (Material Price per Unit Weight)*. In contrast the quantity of presses required for an injection molding line can be calculated as *Q = (Production Volume) * (Cycle Time per Part) / (Operating Time per Year)* . Both cycle time and operating time can be broken down further into simpler design and operational assumptions, but are left as such for clarity. This expression is combined with *E = CRF*[1]*(Discount Rate, Period) x (Price of the Appropriate Press)* to calculate the cost of equipment per year. It should be noted

[1] CRF represents the capital return factor and is explained later in this chapter.

that, in the above two examples, the cost elements are calculated in two different bases, first per unit and second per year. This is acceptable because of the relationship between those two and *N*, annual production volume, mentioned earlier.

In fact, all of the elements of manufacturing cost can be segmented into these two, important categories; those whose contribution depends on the total quantity manufactured during a fixed time period and those which do not. It turns out that the first category, referred to as fixed costs, usually are evaluated more conveniently on a time period basis. Meanwhile, the costs elements in the second category often are conceptualized and assessed more easily on a per unit basis. This second grouping, whose cost contribution is independent of production volume, is labeled as variable costs.

The major fixed cost factors generally fall into one of two groups, those which are one time capital expenses and those which represent recurring payments unrelated to the quantity of parts produced. These generally fall under one of the following headings.

- Equipment Cost
- Building Cost
- Tooling Cost
- Overhead Labor Cost
- Maintenance Cost

Although several of these quantities are weak functions of the quantity of parts produced, this type of breakdown is useful for understanding the root causes of cost. While each of these quantities must be estimated differently for different processes, some general observations can be made. The first factor, machine cost, is assumed to be a function of some size parameter which is relevant for a given process, for example, the maximum compressive force required of a sheet metal stamping press. Extracting cost from such an assumption requires two pieces of information. The first of these is the relationship between the process parameters (the design of the part, the material of which it is made, and how the process is operated) and the minimum necessary size parameter for the manufacturing equipment. This relationship must then be combined with empirical data on how the size parameter translates into a price for such a piece of equipment. The next factor, building cost, generally is estimated like the machine cost, with the distinction that the equipment size parameter must first be resolved into a quantity of building space required and then multiplied by the prevailing space cost. The ability to accurately estimate tooling costs from engineering assumptions has proven to be elusive because of the large number of variables involved. As such, the most successful method has proven to be the use of regression analysis of the tool cost versus explanatory variables like part size, part material, tool material, and annual production volume. Finally, the factors capturing overhead labor and maintenance costs are assumed to have only a weak correlation to the engineering aspects of a particular process. Therefore these quantities often are incorporated as some fraction of another quantity like the machine cost.

Those elements which represent regular recurring payments, like building rent, are easily annualized or converted to any pertinent period basis. However, single payment assets require some scheme to allocate their costs over the duration of production. For this purpose, technical cost models have adopted standard financial constructs to determine the period equivalent cost of purchasing the capital. The most relevant of these is the capital recovery factor,

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

This formula defines the magnitude of cost which must be assessed periodically over the relevant time frame in order to fully ascribe the cost of the capital to a given project. In this relationship, P is the present value of the capital being costed; 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. When applying this equation, the relevant number of periods 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. As an illustration, if a certain style of headlight cover will only be produced over the three year life of its corresponding model vehicle, then the cost of tools, which are purchased for producing only that cover, should be allocated over those three years. In contrast, a building can serve to host the production of many generations of parts and, therefore, should be allocated over a longer time period. Lying in the middle of these extreme timeframes 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 easily permuted in any model of production cost.

The magnitudes of all of the above factor costs are determined strongly by the number of machines required to meet the annual production volume goal. In turn, this quantity, known as the number of parallel streams, is a direct result of the cycle time achievable by a given process, as is shown in the following formula:

$$\#\, of\ Parallel\ Streams = \frac{(Time\ To\ Make\ Parts)}{(Available\ Time)} = \frac{N \times (Cycle\ Time)}{(Available\ Time)}$$

While often involved, a detailed engineering model of the process cycle time can be important for understanding the real cost of manufacture. Given the impact which cycle time has in determining so many cost elements, it could be said that understanding the role of part design and process operating conditions in setting cycle time is the primary goal of any cost model. Recognizing that process and part specifications directly effect operation time is a fundamental premise of technical cost modeling. 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 technical cost modeling.

In complement to process fixed costs, variable cost elements normally arise from the following:

- Material
- Direct Labor
- Energy.

Technical cost modeling assumes that the above quantities can be related directly to the fundamental properties of a process and the manner in which it is operated. Specifically, material costs are set both by the part design and the scrap losses dictated by process and material. The latter quantity captures an issue which is easily overlooked but which can have a significant impact on material costs. Along these lines, it is important to remember that a process' ability to reuse or sell scrap must be carefully accounted for when assessing total material cost. Direct labor, the labor used expressly to carry out a manufacturing operation, derives immediately from the cycle time to produce a part as well as any process or productivity inefficiencies. As with scrap losses, labor inefficiencies must be accounted for when analyzing any real operation. Finally, the energy consumed by a process, while certainly grounded in well established physical laws, is often best estimated from cycle time and a relationship with the machine size parameter mentioned above, in order to reflect the inefficiencies found in real world equipment.

System Modeling

Although the process-based model has proven successful in analyzing the manufacturing cost of a wide range of processes operating on a full spectrum of materials, there are indications that a new synthesis of these ideas is required. This demand arises from the need to address questions associated with complex products. Specifically, as increasingly sophisticated production processes become available, the complex products they generate can be analyzed for cost competitiveness only by taking into account the total cost of manufacture. In this context, complex products are those made up of multiple parts which themselves require multiple manufacturing operations to create. As such, this complexity derives from both the physical complexity embodied in a many subpart product, as well as from the numerous manufacturing operations which must be combined to realize such a product. Ultimately, establishing competitiveness for a complex product requires a systems look at the costs of product manufacture.

An example of the systems implications of material/process change comes from the possible replacement of automotive body structures with advanced composite materials. Several composite manufacturing methods could produce the auto floorpan as a single piece rather than the seven to ten steel subparts which currently are required. However, a comparison of the manufacturing costs of the composite part with the steel parts would be an incomplete look at the cost implications. At a bare minimum, one needs to incorporate the costs of assembling the steel subparts. The analysis, however, should not end at that point. A change of material may allow the use of a different assembly technology when joining the floorpan to the rest of the vehicle. The relevant system is not the floorpan subassembly, but rather the entire vehicle body. As a result, the relative competitiveness of composite and steel parts can be established only when the economic consequences of this process choice upon the entire product manufacturing system are defined. For many contexts, the analysis may even need to extend beyond the traditional boundary of manufacturing to include the derivative effect of material/process change. In such a case, the appropriate system boundary may include several stages in the life-cycle of the product.

The previous sections, following the approaches of traditional TCM analyses, described the problem of cost modeling from the perspective of a process in isolation. When considering how costs are accrued through a collection of processing steps in a manufacturing system, however, some of the above concepts need to be modified and augmented. First of all, those questions concerning the shortfalls of current approaches for modeling manufacturing systems using TCMs must be addressed. From that, it will be easier to propose and evaluate possible solutions.

As mentioned earlier, TCMs have been especially useful due to their adoption of the commercially available spreadsheet as a platform for development. As is well known by most technical or business users, spreadsheets provide a convenient environment for storing data and formulae as well as the results of combining the two. Furthermore, they provide tools specifically targeted at showing the implication of changing input conditions on modeled results. This type of sensitivity analysis is critical in investigating manufacturing cost which, by definition, depends on numerous parameters, many of which are difficult to know accurately at early design stages. When looking at manufacturing systems, however, a new type of sensitivity analysis becomes pertinent. This is looking at the implications of replacing one or several process steps. Such a capability is valuable because functionally equivalent, complex products generally can be created through many different manufacturing paths. On the simplest level, this can occur as in Figure 2.1 where part B can be shaped into final form using process β, γ, or δ. Additionally, it could be that both parts A and B could be replaced by a new part, F, produced

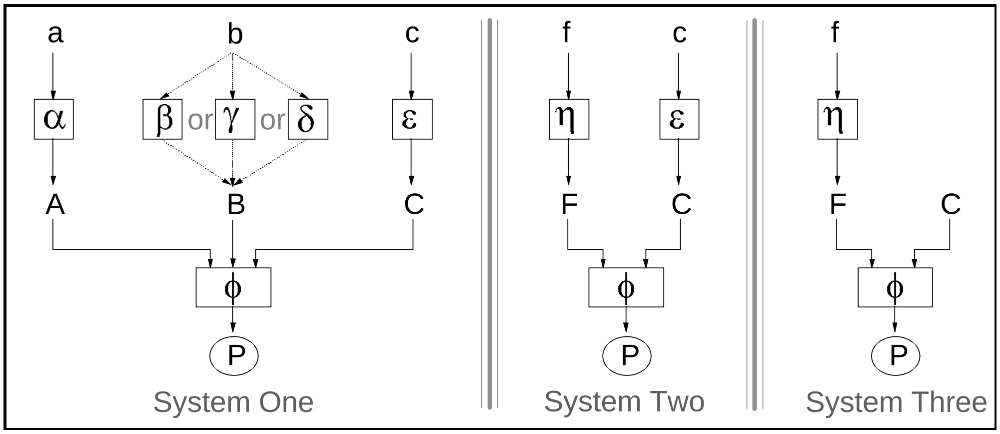

Figure 2.1. Examples of Systems Producing Equivalent Products through Varied Configurations

using an completely different process. (This was the case in the above polymer composite floorpan example.) Similar effects to the model would occur if one expands the options considered to include purchasing the C assembly in its entirety. Regardless of the cause, the end result is numerous possible permutations of system composition and configuration which are able to generate a given product. Most importantly, it is unreasonable to assume that it is possible to enumerate all interesting permutations of the system before model construction. This is most important because, despite the confidence of the modeler or the decisionmaker, either lack of information or simply the effects of time will ensure that system configurations will arise which are of interest and which were previously not considered.

Therefore, it is critical that a system modeling tool be capable of investigating such system changes. Unfortunately, spreadsheets are less adept at handling such changes as compared to their proficiency with parametric sensitivity analyses. Ultimately, this occurs because capturing the effects of configuration change requires varying not only parameters, but also the underlying spreadsheet formulae. The impact of this is shown in Figure 2.2. In this diagram, we see that producing part B through processes β, γ, or δ implies that cost follows the formulae $X_\beta + 2Y_\beta$, $X_\gamma + Z_\gamma$, or $Y_\delta + Z_\delta$, respectively, where X, Y, and Z each represent cost model variables. In a spreadsheet, the options available to investigate the implication of these changes are 1) to do so manually, 2) to construct a complex formula which toggles between the three or 3) to maintain separate copies of each, given certain conditions. The first and third option places the full burden

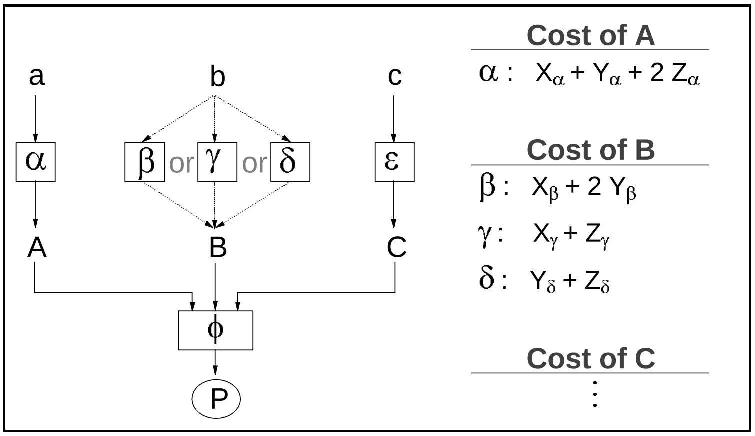

Figure 2.2. Changing System Configuration Alters Model Formulae

of information management on the modeler. The second eliminates this to some degree and would be a satisfactory solution if it were possible to know all of the possible formulae which are of interest from the onset of model development. However, as pointed out above, this is not a realistic expectation since formula variation, in fact, represents changes in system configuration. Furthermore, while these formulae are simple, real cost models are not. Instead, they involve dozens of sometimes complex calculations. Attempting to construct composite formulae or to maintain changes manually in one or several spreadsheets is simply unsatisfactory as a sustainable approach to modeling a generalized system.

Another aspect of system modeling which is important, and which calls to question the use of spreadsheets alone for this purpose, is capturing how the operation of one process step effects the operation of the others in the system. The most important aspect of this behavior arises when process steps are correlated such that the outflows of one form the inflows of the next. Given this common setup, and assuming that there is no accumulation or destruction of flows within the system, the magnitude of all flows is uniquely determined when one flow is specified. It must be emphasized that, as a consequence of this, the magnitude of all flows and, hence, the operational volumes of the processes which drive and demand them are determined by <u>two</u> factors - 1) all of the processes involved and 2) the manner in which they are configured. Any model of a manufacturing system must reflect this behavior. Spreadsheets do provide a convenient way for representing this for simple flow patterns through linking cell data. Unfortunately, even for simple flow patterns the cells must be redefined not only for configuration changes but also in order to query the implications of defining other flows. Finally, this approach is able to handle only unidirectional, well behaved patterns of flows. In general, the representation of cyclic flows creates redundantly defined formulae in the spreadsheet. Given that cyclic flows are pertinent in industrial activities (e.g. the use of prompt scrap in thermoplastic processes), this is a severe limitation on spreadsheets for modeling generalized systems.

A related shortfall of spreadsheets as a platform for modeling manufacturing system economics comes in ensuring that each of the constituent operation steps is ascribed properly to the model which represents it. There are several attributes of cost models and spreadsheet modeling which combine to create this. First, to accurately forecast manufacturing cost, TCMs require large amounts of information to describe fully the relevant operating conditions. As an example of this, Table 2.3 lists the necessary variables from plastic injection molding and steel stamping models. Even with an average 25 descriptive variables, a 10 step manufacturing system requires 250 pieces of data for it to be fully described. Interestingly, within this large data set there are several variables which are relevant to many, if not most, processes. A feature which is common for exogenous economic variables. This, along with other aspects of system data structure, provides an opportunity for computer tools to be used to facilitate the entry of information and to improve the accuracy of the information used. Within the spreadsheet this is accomplished, much like the determination of flow magnitudes mentioned previously, by linking cells of data together and into the cost element formulae for all appropriate processes. Unfortunately, the random access to data provided by spreadsheets which makes this process convenient, also makes it error prone and hard to audit. This can be clearly shown through an example. Figure 2.3 diagrams a portion of a three-step manufacturing system model implemented in spreadsheets. All three processes have different data requirements, but there is some overlap. Furthermore, since all operation steps will occur in the same plant, they should be evaluated using the same labor wage and working days. However, given the proximity of the two values in the spreadsheet, it is easy for these two values to be misassigned in formulae. While, in this example, the error should be obvious, experience has shown that this is often not the case. In

Plastic Injection Molding	Steel Stamping
Part Descriptions	**Part Descriptions**
Part Weight	Stamping Weight
Maximum Wall Thickness	Maximum Stamping Length
Average Wall Thickness	Maximum Stamping Width
Projected Area	Stamping Surface Area
Material Properties	Projected Surface Area
Resin Price	Blank Width
Thermal Conductivity	Blank Length
Heat Capacity	Blank Thickness
Density	Blanks Shaped or Sheared
Material Properties	**Material Properties**
Production Volume	Material Density
Melt Temperature	Material Price
Tool Temperature	Scrap Price
Ejection Temperature	**Operational Variables**
Material Scrap Rate	Production Volume
Product Life	Average Lot Size
Number of Cavities	Product Life
Tool Actions? (Y/N)	Number of Deep Draws
Dedicated Equipment? (Y/N)	Number of Add'l Forming Hits
Cycle Time <optional>	Number of Flange Hits
Tool Cost/Set <optional>	Number of Trim Hits
Cost of Shop Time <optional>	Clean Running Rate
Clamping Force <optional>	Planned, workers unpaid
Productive Time (% total time)	Planned, workers paid
Overhead Burden (% fixed)	Average Die Change Time
Exogenous Economic Variables	**Exogenous Economic Variables**
Direct Wages (w/ benefits)	Direct Wages (w/ benefits)
Working Days per Year	Working Days per Year
Working Hours per Day	Working Hours per Day
Capital Recovery Rate	Capital Recovery Rate
Building Recovery Life	Building Recovery Life
Accounting Life of Machine	Accounting Life of Machine
Working Capital Period	Working Capital Period
Price of Electricity	Price of Electricity
Price of Building Space	Price of Building Space

Table 2.3. TCMs Require Large Amounts of Information to Forecast Cost
Shown is some of the data requirement of existing Injection Molding and Steel Stamping models.

addition, each time a process step is added to the system, these types of connections must be created afresh. Each such instance opens doors to errors.

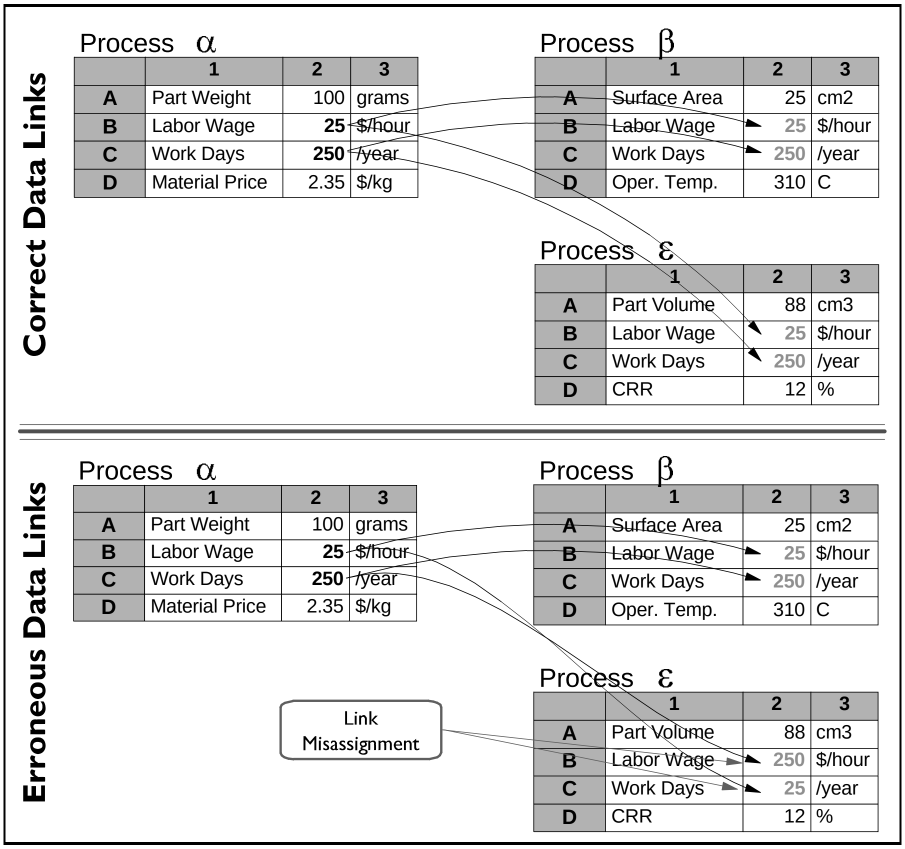

Figure 2.3. Random Information Access Makes Spreadsheets Prone to Data Errors

A final facet of accurately describing a system to model involves not the data, but rather the underlying formulae. Real manufacturing systems often require the same process to be carried out multiple times either progressively on the same part (e.g. multiple painting operations) or separately to produce distinct subparts which come together as a whole. Whatever the cause, the cost elements associated with each of these identical processes must be calculated for their appropriate operating conditions. In order to accomplish this in a spreadsheet, cost formulae <u>must</u> be replicated completely for each instance of the model. This duplication alone creates opportunity for error, but the most serious concern centers around the maintenance of this type of structure. The inevitable dynamic nature of these models <u>ensures</u> that they are constantly improving or at least changing as their mapped technology evolves. When models exist multiple times (e.g., over 100 times in the case of steel auto bodies), they must be updated individually, a process which is very difficult to do and check accurately.

In the end, modeling combinations of processes places additional demands on the cost analyst. In particular, system effects must be taken into account, new configurations must be able to be accommodated, and the large amount of descriptive information must be entered and maintained accurately. While they do provide an efficient means of investigating parametric sensitivity, spreadsheets do not meet any of these criteria in a robust manner. Although some of these shortfalls can be written off as practical in nature, the inability to handle complex flow patterns and the propensity for data and formula errors are fundamental deficiencies. Experience at the Materials Systems Lab in developing large and complex TCMs has shown that even the purely practical aspects of this problem are a true Achilles heel for the realization of accurate analyses. In light of these facts, this thesis details the development of a tool intended to lessen or remove these hindrances from the modeling of manufacturing systems economic.