System Cost Modeling:

Estimating Manufacturing Cost in Large Complex Systems*

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Abstract

This paper proposes a methodology, Systems Cost Modeling (SCM), to evaluate the cost of complex systems with a large number of individual components and subsystems. Simple characteristics associated with each component are used as inputs to parametric estimates of fixed and variable costs, as well as process use time of relevant resources. These estimates are then used to calculate individual component costs, which are then aggregated to the relevant system level. SCM focuses, not on obtaining accurate evaluations of component manufacturing cost, but rather on providing reliable calculations of the overall system cost and enable a robust analysis of the influence of key external parameters such as volume or factor input costs on total cost behavior. To show the use and validity of the SCM, an application of the methodology to the calculation of the supply chain costs for a set of stamped parts is presented.

Keywords
System Cost Modeling, Manufacturing, Complex Systems, Product Development

1. Introduction

The cost dimension is of fundamental importance in the context of product development or process planning stages. Therefore, a number of approaches and methods have been developed over time to enable an estimation of cost during the design stages, when limited information regarding component and process are available (see Sims 1995 for a full review of issues associated to manufacturing cost estimation). As a result, it is now possible to find comprehensive cost modeling methodologies that enable a good understanding of the economic implications of particular decisions related to processes and critical design parameters (e.g. material or production volume) in one or a limited number of parts. But the large majority of today’s products are the result of complex combinations of a rather large number of parts that require an increasingly diverse set of manufacturing operations, as well as a substantial assembly effort. The seat of an automobile, for example, may require 40 different individual parts and more than 10 different manufacturing processes. This complexity is generating a new level of difficulty in terms of cost estimation for the complete system, requiring new approaches in terms of system cost modeling.
Most existing cost models, because they have been developed to provide good accuracy in estimating the cost of individual parts, require a large number of detailed information about the component and the processing conditions. An average individual process based cost model may require the introduction of 25 descriptive variables (Kirchain 1999, chapter 2), which would lead to having more than 10,000 variables to be accounted for in the seat example described above. This makes the estimation process extremely difficult and time consuming. Moreover, there are a number of situations where extreme accuracy in the component cost estimation is not the desired feature. For example, if the objective is to understand how car volume will affect total seat cost, some degree of error in individual component cost may be tolerated, as long as the total seat cost is within a certain error margin, with the key interest being an accurate display of the relative variation in cost due to volume changes. To respond this new set of challenges in cost estimation, there is a growing effort towards expanding nature of cost models, so that they can be used to estimate costs for larger and ever more complex products (Han 1994; Kang 1998; Kirchain 1999).

This paper aims to contribute to this literature. It proposes a method for estimating cost of complex systems, where a large number of components are present. It uses a bottom-up approach by incorporating basic part and processing information to build a manufacturing cost approximation. The method, called System Cost Modeling, is a semi-parametric estimation procedure, that is built on a set of observed regularities in the relation between component characteristics and processing equipment costs, as well as notions of activity based costing. The paper will discuss existing costing methods, describe the SCM approach and then test the methodology against existing detailed cost estimations procedures.

2. Estimating Manufacturing Cost

2.1. Top down approaches to estimation of component cost

The earliest and still one of the most widely used techniques for evaluating the cost of manufacturing processes are simple rules of thumb. Designers or engineers with experience with the relevant technologies and processes usually develop rules that relate key variables of the process or material to the final cost (Busch and Field III 1988). For example, markup over
materials cost is common among such rules. Another common manufacturing cost estimation procedure is to use accounting principles. A particularly popular application of these principles is activity based costing (ABC), which attributes direct and overhead costs to products and services on the basis of the underlying activities that generate the costs gathered from firm accounting information (Cooper and Kaplan 1988). Accounting ABC is based on historical and descriptive information. Therefore, when successfully applied, it enables a good understanding of existing critical cost drivers and it allows more accurate decisions of pricing and marketing. Nevertheless, because of its retrospective and contextual nature, ABC it is of limited help to engineers and designers concerned with improving manufacturing lines or choosing between alternative materials in during design.

The lack of accuracy and the reliance on contextual data to estimate manufacturing cost has prompted the development of more accurate methods, and especially ones that enable an estimation of cost at the design stage. Cost estimation during design, especially in early stages, is a difficult task because there is limited information about the characteristics of the product. It is also of crucial importance because design decisions condition most of the product cost. According to O’Grady et al. (1991), Ford estimates that design decisions determine 70% of the production cost.

Two different approaches have been followed in the development of manufacturing cost models. The first can be characterized as a top-down approach. This method aims at establishing a relationship between cost and critical product and/or process parameters. These range from high-level functional attributes to detailed manufacturing characteristics. Bode (2000) provides a good example of high-level functional estimation. He tests the relationship between the cost of a personal computer and the size of the memory and hard disk, the type of CPU, the speed, presence of a CD-Rom, screen type as well as production volume. By contrast, Mileham et al. (1993) relates cost of an injection-molded part to product weight, production volume, cycle time and machine size. Regardless of the desired level of abstraction, all these methods entail gathering information about cost and relevant parameters for a large number of items in the same category or group and then using a statistical method to establish the desired relationship between both sets of information.
Parametric regression based cost estimation methods are the most common (Cochran 1976; Datar, Kekre et al. 1993; Mileham, Currie et al. 1993; Shtub and Versano 1999). The cost engineer will a priori determine a cost function with relevant parameters based on his experience and then derives it through statistical regression methods using past case data. The major difficulty of these methods is that the cost engineer must have a sufficiently accurate cost function a priori to be able to make the estimation. When such functional relationship is not obvious, these methods may not yield adequate results. As a consequence of these shortcomings, research in top-down estimation methods has evolved towards experimenting with non-parametric approximations (Asiedu, Besant et al. 2000), neural network calculations (Shtub and Versano 1999; Bode 2000; Wang, Stockton et al. 2000) and pattern recognition approaches (Rehman and Guenov 1998; Ten Brinke, Lutters et al. 2000). Neural networks fit curves through data without being provided a predetermined function, estimating both the shape and parameter values of the cost function in one step. Therefore, they are able to detect hidden functional relationships between product attributes and cost, including relationships unknown to the engineer. In pattern recognition, or case based reasoning, the features of the proposed product are matched against those of all products in a database of historical information to match similar cases and compute the likely cost. As one would expect, both neural networks and pattern recognition are likely to be advantageous when compared to parametric estimation in the early design phase, when the cost engineer has more difficulty in establishing a sufficiently accurate functional relationship between product attributes and cost.

While top down methods go a long way in terms of reaching reasonable estimates for manufacturing cost, they share important limitations, regardless of the particular technique employed. The first is the need for large number of observations, for which cost and features need to be available to allow statistical estimation. While this may be the case for established technologies such as stamping or injection molding, it is hardly the case where new technologies are concerned. As a result, such methods may of less interest if one is interested in understanding, for example, the cost implication of replacing the steel stamped door of a car by a new composite one, for which there are few equivalent products in the market. A second limitation is that these methods are not amenable to a study of how processing conditions affect cost. For example, if a particular firm is deciding, not only what material to use, but also if the
plant should be in Mexico or the US, it may be interested, not only on the intrinsic cost tradeoffs between technologies, but also on how factor conditions affect each potential solution. With benchmark data typically available only for developed markets, such as the US, Europe or Japan, it might be difficult to use any of these methods for an adequate assessment.

2.2. **Bottom up estimation of component cost**

To allow greater flexibility and accuracy, the alternative cost estimation approach has been to use a bottom up assessment of cost, in particular process based cost models. Process based cost models map product characteristics with processing conditions to evaluate unit cost drivers. These models have been developed for a number of manufacturing processes and with various levels of detail (Busch and Field III 1988; Boothroyd, Dewhurst et al. 1994; Clark, Roth et al. 1997; Chan and Lewis 2000; Locascio 2000; Kirchain and Clark 2001).

Process based cost modeling starts with an identification of the relevant process steps required to manufacture a particular component. The fender of a car, for example, may start as a steel sheet coil that is blanked, then stamped, and later painted. For each identified step, all relevant cost drivers are estimated. Cost is separated into fixed and variable components. This division reflects the fact that variable costs can be directly associated with the production of every unit of output, thus increasing roughly linearly with production volume. On the contrary, fixed costs remain constant until production capacity is reached, whereupon more equipment is required. These categories can then be further subdivided into variable costs of material, direct labor, and energy; and the capital costs of main and auxiliary equipment, tooling, building, maintenance and overhead. The items considered typically include those related only to manufacturing in order to maintain consistency with conventional views on cost. The critical difference with the accounting approach noted above is that values underlying each of the categories are a reflection, not of accounting information gathered at a plant, but of how engineering process knowledge influences each of these cost accounts.

A good example of simpler estimation techniques for process based models is Locascio (2000). To generate a cost model for an electronics assembly line, she first identifies 12 individual process steps. For each step, she uses historical data on processing conditions to estimate how
Process cycle relates to product characteristics. This time is then used together with information on and capital allocations to estimate unit cost. More complex process cost model estimation methods use engineering relationships to estimate relevant parameters, in particular cycle time and equipment characteristics. For example, in injection molding, physical laws dictate that clamping force required to hold the dies closed during mold filling must be greater than the force generated normal to the plane of die separation. This force can be related to the filling pressure and the cross section in that plane of the part being produced. With enough information, the relationship between the clamping force and these design parameters can be modeled to an extreme level of detail. The equipment clamping force is the key cost driver determining the cost of the equipment. Such a relationship can then be obtained from vendors. A similar reasoning can be applied to cycle time. In injection molding, cycle time is governed by the time to inject the material in a cavity and then the time it takes for it to cool down. Engineering calculations based on the temperature of the material and the mold, the density of material as well as key design features of the part can be used to estimate cycle time. Busch (1987) estimated such relationships and used them to build one of the initial cost models, to evaluate the cost of injection molded parts.

Process based cost modeling is a flexible tool to analyze the manufacturing cost implications of different strategies, business conditions and product characteristics. The models enable wide experimentation and analysis, critical to evaluate relative strengths and weaknesses of alternative paths, or to pinpoint critical engineering or economic factors affecting cost, particularly in early stages of design (Boothroyd, Dewhurst et al. 1994; Humphreys and Wellman 1996; Clark, Roth et al. 1997; Kirchain and Clark 2001). A critical application for these models is precisely in the assessment of the cost characteristics of new technologies. For example, Chiango et al. (2000) analyze the economics of steel powder production by rotating electrodes; Bhatkal and Hannibal (1999) do the same for Powder Metallurgy. A related application is the comparison of a new technology or material with existing solutions. Busch (1987) looked at the economic impact of using different polymer resins in injection molding and Busch & Field (1988) compared the cost of injection molding, blow molding, thermoforming and structural foam molding for the manufacturing of panels. Kelkar et al. (2001) used a set of models for metal processing, including roll-forming, bending, stamping, casting, extrusion, hydroforming, as well as
assembly, to compare the costs of the traditional steel car body in white with alternative aluminum designs; Mangin et al. (1993) compare performance and cost of traditional and ceramic materials for automotive engine applications. Yet a third level of application for these models is the study of design decisions. Ulrich and Pearson (1998) used detailed cost modeling of injection molding, steel stamping and assembly to compare the cost implications of design variations across a set of coffee makers. Fixson (2002) uses several process based cost models to study how product architecture influences cost, looking at the example of car doors.

Despite this wide array of applications, process based cost models have an important common limitation: they can be extremely data intensive. The estimation for each component and process requires detailed data on process conditions and part geometry to be able to generate good results. For example, an injection molding cost model may require as much as 15 inputs related to part and process alone. As a result, it is not surprising that these models are mostly used so far to compare individual or small groups of parts, and usually for pairs of processes, although in limited cases they’ve been used to analyze large collections of parts or entire automobile bodies (Han 1994; Kang 1998).

2.3. **Estimating the cost for large numbers of components**

Most traditional applications of process based cost models involve understanding the economic implications of changes in process or critical design parameters (e.g. material, production volume, factor condition) in a limited number of parts and for one or very few competing individual processes to (Clark, Roth et al. 1997). Nevertheless, the large majority of today’s products are the result of a complex combination of parts that require numerous operations in their manufacturing as well as a substantial assembly effort. The seat of an automobile, for example, may require 40 different individual parts and more than 10 different processes. Given that an average model may require the introduction of 25 descriptive variables (Kirchain 1999, chapter 2), more than 10,000 variables would have to be accounted for. This makes the estimation process extremely difficult. As a result, there has been a recent effort towards expanding the use of process based cost models so that they can be used to estimate costs for more complex products (Han 1994; Kang 1998; Kirchain 1999).
The initial problem resulting from an increase in the number of variables is handling the information. Traditional models have been implemented in spreadsheets. But manipulating large number of variables in spreadsheets is not only very time consuming and inefficient, but it also very prone to errors. To address this problem, Kirchain (1999) developed an application to support the use of process models in an object-oriented database environment. The computer tool created a uniform data structure that describes each part in a system and the procedures that emulate the behavior and interrelationship of those parts. A case study of the automobile recycling infrastructure was used to demonstrate the applicability of the tool.

But, while the use of computer tools facilitates the problem associated with manipulating and processing large amounts of information, it does not address the problem of data collection. Gathering or constructing detailed design and processing data for a large number of parts is very difficult. Detailed design and processing information required as inputs for the cost models are likely to be scattered among various persons and departments in a large organization. Furthermore, the supply chain may become disperse, with various firms responsible for different components, rendering the process of data collection virtually impossible.

For a manufacturing firm, a high level of detail in cost estimation can be very important for rigorous competitiveness assessment, particularly at the manufacturing stage. If this is the case, companies assemble large teams of engineering and purchasing people devoted to estimating the cost of each individual part. Automotive is a good example of an industry where this is often the case. However, for the overall assessment of a system in early stages of development, or to investigate the generic impact of changes in factor conditions, such a level of detail is not desirable or sometimes not possible to achieve. Therefore, it is important to find methods to approximate the estimations. At one extreme it is possible to go back to the top down techniques mentioned in the previous sections. However, it might be reasonable to expect that solutions that reduce data requirements without compromising the logic and the mechanisms underlying the process based cost model are possible and might be preferable if there is an interest in the impact in cost from changes in the underlying conditions, such as wages or capital cost.

A potential approach to this problem is the extrapolative method, proposed by Han (1994) and further developed by Kang (1998), to estimate the cost of the body-in-white (BIW) of an
automobile. Instead of modeling approximately 150 parts existing in a BIW, a set of categories were determined and a representative part to be modeled in detail through detailed process based cost modeling was chosen for each category. The categories were determined according to differences in part geometry, size and forming complexity. The rest of the parts in the BIW were assigned to each of the categories. Assuming that all parts were formed in a similar fashion, their cost was estimated using weight ratios and identical processing conditions to those used for the representative part in each category.

The two applications show that the extrapolative method can be extremely useful when the parts have similar processing conditions and common characteristics that can be used to establish the relative differences. The method may not be so accurate if processing technologies and conditions are very diverse. A good example of this situation is the attempt to model all 3000 components of a car. Unlike the BIW, there is little common ground between components except the fact that they are all manufactured according to a number of processes. While the BIW may only require a handful of technologies, the 3000 parts of the car require several dozen processes. The approach for these more complex cases still may be to model all the components, but to reduce the requirements in terms of the information and the modeling detail associated with each component. This is precisely the approach of the system cost modeling methodology described in the next section.


The SCM method aims at establishing a systematic way to estimate cost functions for complex systems, such as the interior or the chassis of a car, where multiple processes and diverse components are present. The cost function is grounded in engineering based estimates of the manufacturing and assembly cost of its individual components, aggregated over subsystems. Unlike most existing cost estimation methods, which aim at obtaining an accurate evaluation of the manufacturing cost at an individual component level, SCM focuses on providing reliable calculations of the overall system cost and the influence of key parameters (such as volume and factor input costs), on the cost behavior.
When comparing manufacturing costs at the individual component level, accuracy and detail in the estimates is crucial for the relevance of a particular methodology. This is precisely the objective of the traditional process based cost models (also known as TCM-Technical Cost Models) described in the previous section. SCM follows the same logic and estimation pattern of TCM, but it reduces the information intensity required and, as a result, it also provides less precision in cost estimates. Therefore, although SCM provides individual component cost, values at this level will only be on the right order of magnitude, limiting the ability to establish comparisons between individual parts or technologies. Nevertheless, when comparing system costs, the level of idiosyncrasies is high enough that order of magnitude and trend are the relevant parameters that a researcher or practitioner may be concerned with. A typical application of SCM is the evaluation of the impact of wages or capacity utilization on a system cost, but not to compare the use of aluminum versus steel in the manufacturing of a car door beam.

SCM is based on a systematic evaluation of individual component costs. It is important to detail how this evaluation is done and how the individual and aggregate costs are established. Cost estimation requires a careful evaluation of two aspects:

- The cost factors involved in a particular manufacturing process.
- The process time use associated to a particular technology and component

++++++++++ Insert Figure 1 here ++++++++++

The critical SCM approach to simplify traditional process based cost modeling techniques, illustrated in Figure 1, is to use four simple metrics as the basis for establishing all the cost drivers of an individual part. The metrics considered:

- **Weight.** This indicator is readily available or it is easy to estimate for any component, making it a very natural choice. It’s important for the material cost estimate and serves as a
proxy for the volume of the component, often a major factor determining the characteristics of the required processing equipment and tooling.

- **Material.** Information is usually directly available for each component, even when several materials are mixed together. Moreover, it is critical to estimate the material cost, which is often a significant portion of the total.

- **Complexity.** Detailed information regarding shape, thickness and other factors used to calculate equipment characteristics are substituted by a three level complexity factor, estimated by judgment. Level 1 corresponds to simple components where their size is the major factor affecting processing; higher levels of complexity imply more detail or additional features that require more complex (and therefore more expensive) equipment.

  An example is a convoluted injection molded part, which would require (a) a more complex and therefore more expensive tool; (b) higher pressures to cope with the complex mold that result in a larger more costly machine; (c) longer times to fill the cavity, affecting time utilization of equipment as well as labor; (d) greater scrap losses due to engineering trim or rejects.

- **Process.** To manufacture each component, a particular process is assigned. This process is either provided or determined knowing the material and analyzing the role the component in the overall system.

These metrics are used directly to determine equipment cost, tooling cost, labor usage, cycle time and material needed for the manufacturing of a component. These estimations, together with local factor conditions enable an evaluation of the fixed and variable unit costs associated with each component. Cost estimations for individual components are then added and assembly costs are incorporated. The following sections detail the method of calculating the costs, where the traditional accounting division between fixed and variable costs highlighted above is used.
3.1. Fixed Costs

Fixed costs are associated with aspects of the process that cannot easily be changed within the time frame relevant for the analysis, and are independent of the level of our control variables or the rate of inputs or outputs. Even if nothing is to be produced, these costs will still exist. Typical examples of fixed costs are the building or the machines used for production.

**Equipment Cost**

The technical estimation of equipment costs, illustrated in Figure 2, is often done in two steps. First, the features of the component to be formed are used to identify the required key characteristics of the equipment to be used in the manufacturing process. In the second stage, this key characteristic is used to estimate the cost of the equipment.

For each manufacturing process, the main equipment that is used to achieve the desired transformation process is usually characterized by one major feature (see Kalpakjian 1995, for detailed explanations of these features and their importance). For example, in the injection molding process, this key characteristic is the machine Clamping Force. The Clamping force is applied by the machine to keep the dies closed during injection of molten plastic in the mold cavities. Since there are typical pressures inside the mold necessary to assure the desired part characteristics, the clamping force determines the maximum size of the part. Likewise, die casting machines also have the force that keeps the die closed as the limiting factor. Therefore, they are also characterized and rated as a function of the clamping force. A similar situation is found in most other technologies.

This key characteristic can often be estimated from component features such as volume, material, and shape that will exist from component design specifications. For example, when injection molding, physical laws dictate that clamping force required to hold the dies closed during mold filling process must be greater than the force generated normal to the plane of die
separation. This force can be related to the filling pressure and the cross section in that plane of the part being produced. With enough information, the relationship between the clamping force and these design parameters can be modeled to an extreme level of detail. Again for the same example, previous work (Busch 1987) has shown that the press clamping force can be accurately estimated by:

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

Similar relations can be found for other technologies, enabling an estimate of such key equipment characteristics. The second step then, is to relate this computed characteristic to equipment cost. For the injection molding example, the required clamping force can used to gather information regarding machine prices directly from equipment suppliers. Alternatively, information for different forces and associated costs can be gathered from a number of suppliers, and a statistical relationship between the force and the investment in equipment can be established (Busch 1987; Boothroyd, Dewhurst et al. 1994, Chapter 8). This statistical relations allows to complete the relation from part characteristics to equipment cost.

This type of estimation method can be performed for virtually any technology, with the relevance of each design parameter depending on the particular process under consideration (see Han 1994; Kirchain 1999 for a discussion of the multiple applications of TCM). If instead of injection molding, the above consideration would be for stamping, the relevant component features to estimate the punching force would be material, area and the depth to length ratio. But such detailed estimation process is precisely associated with the detailed estimation procedure found in process based cost models. As explained, it requires fine data such as wall thickness of depth to length ratio.

The SCM approach to estimate equipment cost involves two critical simplifications from this traditional cost modeling techniques. The first is to aggregate detailed component information associated with physical characteristics into the four simple metrics discussed above. The second is to establish a direct relationship between these metrics and equipment cost, bypassing the step of estimating the key characteristic of the equipment described above.
The simplification is illustrated in Figure 3 and the differences to traditional cost modeling can be perceived by comparing it with Figure 2 shown before. Instead of using detailed geometrical characteristics to estimate equipment cost, SCM relies on component weight and complexity. For the particular process assigned to a component, these two metrics are used to derive equipment cost. SCM proposes a functional form to relate component features and equipment cost following a logarithm:

\[ Cost = A(\text{Weight})^b(\text{Complexity})^c \]

This functional form (with \(b,c<1\)) is a generalization of previous work from several authors on the area of cost estimation (Busch and Field III 1988; Boothroyd, Dewhurst et al. 1994; Han 1994; Humphreys and Wellman 1996). The use a logarithmic relationship to scale costs based on a key parameter, in this case weight, has been widely used in the chemical industry (a recent summary of several work done in this area can be found in Humphreys and Wellman 1996, chapter 1). But unrelated manufacturing cost estimation research shows that logarithmic relationships between component weight and equipment cost seems to hold in a number of other circumstances.

Table 1 illustrates how the relationship between weight and equipment cost becomes logarithmic due to composite effects of a linear and a logarithmic function on the estimation steps from weight to equipment key characteristic and then to equipment cost. This type of behavior is observed for diverse technologies, suggesting the generic choice made in (1). The end term on the right hand side of the equation is used as a modifier to account for the impact of complexity on the capabilities of the equipment and, therefore on its cost.
Assuming that the relationship proposed in equation (1) holds, the relevant parameters $A$, $b$ and $c$ have to be estimated. Following previous examples, an obvious estimation method would be to perform regressions of observed equipment cost on the relevant parameters for a number of parts and processes. Unfortunately, given the pioneer stage of the method, data for such estimation is still not available. Therefore, the choice was to have an initial estimate of the three coefficients in the proposed relationship based on a three-point estimation.

While any three points can be used, the particular evaluation that was selected follows the procedure described below:

1. **Identification of extreme points.** The choices for two of the points were the extremes. For a range of components for which equipment cost is to be estimated, the extreme points are such that the component with minimum weight ($Min\_Weight$) and complexity equal to one is associated with the minimum equipment cost ($Min\_Cost$), and the component with maximum weight ($Max\_Weight$) and complexity level equal to three corresponds to the highest equipment cost ($Max\_Cost$). This uses the weight and complexity information for the set of parts manufactured with the relevant technology. Equipment costs for the extreme parts is gathered either from published sources or directly from equipment suppliers.

2. **Mid point estimation.** An additional point is required to complete the estimation. The strategy was to choose a point that would define the relative importance of complexity and weight in establishing equipment cost. The mid point corresponds to a simple part (complexity equal to one) with maximum weight. This point defines the share of the equipment cost that is defined by the weight as opposed to complexity. If the equipment cost for this part is close to the maximum cost, then most of the cost is defined by weight; if its closer to the minimum cost, then complexity is the determining factor. To make this tradeoff explicit, equipment cost for this point is presented as a share of the difference between the values gathered for the extreme points defined before, instead of an absolute value. This share value is labeled as a weight, $Factor$.

Given this methodology, the parameters $A$, $b$ and $c$ in equation (1) are then defined through the following equations:
\(2\) \(\text{Min\_Cost} = A(\text{Min\_Weight})^b (1)^c; \text{Max\_Cost} = A(\text{Max\_Weight})^b (3)^c\) for the extremes

\(3\) \(\text{Min\_Cost} + (\text{Max\_Cost} - \text{Min\_Cost})\times \text{Factor} = A(\text{Max\_Weight})^b (1)^c\) for the mid-point

Where Factor is the share of the cost difference explained by the complexity level. Solving these equations results in:

\(4\) \(b = \log\left(1 + \left(\frac{\text{Max\_Cost}}{\text{Min\_Cost}} - 1\right)\text{Factor}\right)/\log\left(\frac{\text{Max\_Weight}}{\text{Min\_Weight}}\right)\)

\(5\) \(A = \frac{\text{Min\_Cost}}{\text{Min\_Weight}}^b\)

\(6\) \(c = (\log 3)^{-1} \log\left(\frac{\text{Max\_Cost}}{A.\text{Max\_Weight}}^b\right)\)

These estimation steps become clearer with an application to a particular technology. Stamping (using Tandem presses) will be used as an example. Imagine that the objective is to model all the components in a car. Typically there are over 1000 stamped metal components in the vehicle. For each of these, a level of complexity from 1 to 3 is assigned and the weight is determined.

1. **Extreme point identification.** An observation of the parts reveals that weights range from a few grams to 15 kg. Eliminating the parts below 1kg that are manufactured using progressive die stamping technology, the relevant parts will have a weight ranging from 1kg \((\text{Min\_Weight})\) to 15kg \((\text{Max\_Weight})\) and complexities from 1 to 3. Literature on stamping and direct interviews with equipment suppliers establish that a line of tandem presses required to handle components weighting 1kg and with minimal complexity costs approximately US$1,500,000 \((\text{Min\_Cost})\). The cost of a press line to stamp a 15kg part of high complexity was estimated to be US$10,000,000 \((\text{Max\_Cost})\). These values establish the extreme points used in the estimation of (1).

2. **Mid point estimation.** To establish the mid point, it was assumed that 80% of the cost difference is determined by weight (this is equivalent to having Factor = 80%), while only 20% is determined by part complexity. In other words, a part weighing 15kg with a
complexity level of 1 requires a press line that costs approximately US$8.3 Million (80% of the way from $1,500,000 to $10M).

With this information, equipment cost can be mapped to the component characteristics using equations (4) to (6), resulting in \( A=1500 \), \( b=0.63 \) and \( c=0.17 \), for results in thousands of dollars.

The evaluation for the example of this stamping technology is represented in Figure 4. With this evaluation method, a moderately complex stamped part (with complexity level equal to 2) weighing 8kg needs a press line that costs approximately US$6.276 million.

The equipment cost estimated through the steps described above usually has to be adjusted to take into consideration two aspects. First, auxiliary equipment costs may have to be considered. Quotes from equipment suppliers often do not include complementary machinery such as fixtures, conveyors and workbenches, among others. Because it extremely difficult to have an accurate estimate of these costs, they are usually considered as a percentage of the investment in the main equipment, with ranges depending on the level of automation that will be used to loading, unloading and conveying. These values are usually gathered directly using industry estimates. On average, auxiliary equipment is found to be 25% of the main equipment value. The second correction is for installation costs. Any industrial equipment requires careful installation, ranging from electrical power and dedicated supplies to precise positioning in the building and training of the workers. These are relevant additional costs beyond the equipment value. Like auxiliary equipment, they are difficult to estimate and are usually considered to be a fixed percentage of the equipment cost. Again, an average installation cost gathered from industry quotes is 15% of main equipment cost. With these average values, the 8kg stamping example mentioned above would require an additional $1,569,000 in auxiliary equipment and $941,000 in installation. This process described in detail with the stamping example is then replicated for all other technologies considered in the analysis of a relevant system cost.
Another important element of equipment cost is tooling. Tooling cost is probably the most difficult value to estimate because it is unique for each part that is produced. The main difficulty arises from the inability to completely describe tool complexity using only limited and standard component description inputs. Geometric details can make a tool extremely difficult to produce and, therefore very expensive. The approach used with more success is to regress tooling cost on certain material, geometric, durability and conformability characteristics of the tool, based on historical information for each relevant process (Busch 1987; Busch and Field III 1988; Boothroyd, Dewhurst et al. 1994, chapter 8 to 10). Again, the traditional method is very intensive in information input.

The process used in the SCM approach to calculate tool cost is similar to what was described for equipment cost. Again a logarithmic relationship between component weight and tool cost of the type presented in equation (1) is assumed, using complexity as a cost modifier. This functional form is reasonable because the major drivers for tool cost are the part surface area (Busch 1987; Boothroyd, Dewhurst et al. 1994) and weight which are directly proportional to the volume. This argument is similar to the one used in the chemical industry to estimate cost as a log function of capacity (Humphreys and Wellman 1996, chapter 1).

The difference here is related to the effect of complexity on overall tool cost. Complex components require the tool to have particular characteristics that can substantially change its cost. In stamping, for example, a tool with moving parts to accomplish a particular component feature may cost as much as two times that of a component with similar size but with a simple shape (Han 1994). A similar situation can be observed for casting or injection molding (Busch 1987). Therefore, when considering equations (2) and (3) for estimating tool costs, the Factor value that determines the relative importance of complexity in the cost will be different, assigning greater relative importance for complexity.
Like before, calculating individual tool costs requires the steps described for the case of equipment costs: the range of component weights and complexities has to be registered, information from suppliers on the equivalent range of tool costs has to be collected, and new three point estimation is performed, with the new values and assumptions regarding the weight factor value. Given this information, the parameters \( A \), \( b \) and \( c \) in formula (1) can be calculated from equations (4) to (6). The visual representation of these calculations for the example of tooling for tandem stamping is presented in Figure 5, where the base value for the factor considered in the estimation is 50%, dividing equally the importance of weight and complexity level. Similar steps are taken for all other relevant technologies.

**Other Fixed Cost**

In addition to equipment costs, there is a set of other factors such as building, overhead and maintenance that only have a weak correlation to the engineering aspects of a particular process. Therefore, they are often incorporated as a function of machine and tooling cost.

*Building Cost* depends directly on the equipment that is necessary to assure the manufacturing process. On the one hand, more equipment requires more space; on the other hand more complex equipment may require greater care with the surrounding environment (e.g. precision leveling of the floor), both resulting in greater building cost. Therefore, this cost can be treated as share of equipment cost. It can also be estimated given the amount of space that the equipment will occupy, with the surface area value for industrial operations obtained from industry or real estate sources. Consultation with industry and previous studies has placed building cost as 4% to 8% of equipment cost. The base value considered for the study is 6%.

*Maintenance Cost* is considered as a fixed percentage of the cost associated with equipment, tooling and buildings. Although formal stochastic models of machine failure and maintenance schedules exist (Gershwin 1994), this level of sophistication is often not helpful when the object of the analysis is cost and not specific shop floor planning. The ratio to equipment cost approach is used because maintenance expenses are often correlated with the cost of the original equipment. A 10% value is often found as quotes from suppliers.
Overhead labor costs consist of supervisors, janitors, accountants and other personnel not directly involved in the production process. This is a value for which it is impossible to have an accurate estimate since it depends on the human resources practices of each company. Because of the high variability, it is assumed as fixed percent of direct labor. Fixed Overhead includes all other fixed costs of the company, including the equipment used in the administration and management. It is valued as a percentage of the equipment cost. The values assumed as baseline were 50% of overhead labor over the direct production labor cost (detailed below) and 25% equipment cost for fixed overheads.

Annualizing Fixed Costs

Fixed costs extend beyond the one-year time frame currently used for analysis. Therefore, all investment is annualized, considering a level of discount rate and a capital recovery period. The approach used is the economic notion of opportunity cost. Investments in fixed capital, including items such as equipment and building, could have been applied elsewhere in the economy rendering a reference annual income during the period of the investment\(^1\). As a result, each of the fixed cost drivers described above has an annual equivalent that is used in the evaluations. This will be considered as the Annual Fixed Cost. Although tooling is also considered an annualized investment, it will be dedicated to a specific part. Therefore, the recovery period is the life time of product and not the of the equipment.

3.2. Variable Costs

Variable costs depend on the rate or volume of production. They are measured based on either inputs or outputs of production. Typical examples of this cost are raw materials or energy consumption. Some of these costs can be directly attributed to a particular part (e.g. raw materials), while others (e.g. energy) have to be converted through some common metric, usually time.

\(^1\) For example it could be loaned to someone at a market rate, or invested in a portfolio of securities.
Material Cost

Material cost is one of the most important cost drivers. This cost depends on the quantity of material that is bought, mostly driven by the weight. Nevertheless, an accurate treatment of the material cost has to take in consideration rejects and scrap that result from the different steps of the production process. Because there is a market for scrap, the amount sold has also to be deducted from material costs. The major aspect influencing the levels of engineering scrap rate in a component is its complexity.

The SCM approach is to link the level of complexity associated with each component to a given percentage of material that is scrapped (for each good unit produced). Typical values considered are 15%, 30% and 45% for levels of complexity of 1, 2 and 3 respectively, but this are adjusted for individual technologies. Total material cost involves the weight of each component summed with the respective share of scrap, both multiplied by unit material cost that was gathered from published sources.

Direct Labor Cost

Another important variable cost is labor cost. This cost includes the workers that are needed to operate the equipment required in the relevant manufacturing process, as well as those that assemble individual parts and components into systems. Direct labor cost is a function of the man-hours per year used to produce the part and the wages (and benefits) they are paid. This calculation takes in consideration the intrinsic characteristics of the technologies chosen to perform the relevant operations, particularly in what concerns automation, but it also depends on time allocation patterns chosen by the management of the company.

A logarithmic relationship similar to (1) is also used to estimate manufacturing labor costs. The important difference is that the number of workers and not their cost is written as a function of component characteristics:

\[
(7) \quad \text{Number of Workers} = A(\text{Weight})^b (\text{Complexity})^c
\]

To understand the difference in the approach it is important to note that the market for equipment is global, with the same suppliers quoting similar prices regardless of the location of the plant.
This makes it possible to establish the unique relationship between equipment cost and part characteristics proposed in formula (1). On the contrary, labor market is local. Therefore, it is not reasonable to write labor cost as a function of part characteristics. But workers required for the relevant manufacturing activity are directly associated with processing equipment. In fact, information on equipment characteristics often includes ranges for the number of workers required to operate it depending on the characteristics of the component being manufactured. This leads to the modeling choice to have the number of workers as a function of component characteristics.

The solutions to equation (7) can also be given by (4), (5) and (6), provided that the necessary adjustments are done. This means that the values of maximum and minimum cost are now associated with the maximum and minimum number of workers, while part weight and complexity are the same as before. Factor values determining the relative importance of complexity and weight for labor utilization have also to be chosen for each technology. Manufacturing labor costs are then calculated multiplying the worker estimates by the unit wage of the region.

Other Variable Costs

- **Energy Costs** are simply a function of the price of energy, the machines consumption rates and the number of hours that they work.

- **Inventory Cost** results from having raw materials, work in process and final goods immobilized in the company. This involves an opportunity cost tied to the value of the immobilized product, as well as costs related to storage and potential negative implications to the company organization (Womack and Jones 1996). This cost is often evaluated by evaluating material flow in the company or through accounting techniques.

3.3. Valuing the Process Time Use of Resources

The methods described in the previous section establish the methods that lead to an evaluation of the cost of the resources required to manufacture a particular component. But previous sections have not discussed how the time it takes to manufacture an individual component, or to reach a
particular annual production volume, affects its cost. In fact, while time is certainly not important for material costs, it becomes critical for fixed costs, which are associated with resources (e.g. equipment) with a useful life that extends beyond one. Therefore, it is important to establish the concept of *Process Use Time (PUT)*. The idea of PUT is that the cost of resources may be determined by the cost of using them for the amount of time required to reach the desired production volume. PUT becomes a critical control variable in a manufacturing system because increasing process use time is associated with the use of more equipment, additional workers and energy utilization and, as a result, accrued cost (Sims 1995).

*Cycle Time*

The critical variable determining time usage is *Cycle Time*, the time between two consecutive parts coming out of a production line. In process based cost models, Cycle Time is calculated using information on the technological constraints that determine processing time. For example, in injection molding, cycle time can be effectively divided into three separate segments: injection or filling time, cooling time, and mold resetting time. Given a particular mold design and machine clamping force, these times can be calculated through an analysis of polymer flows in the mold cavity. While precise estimates using computational models can be achieved using specific software (Clark, Roth et al. 1997), a more expedite solution with cost estimation objectives is to establish a statistical relationship between critical variables. Previous work (Busch 1987) has established that cycle time can be regressed with a good degree of confidence on cooling time and weight of a particular part. Part geometry and material characteristics are enough to establish weight and, using transport theory, calculate the required cooling time for the part (Ballman and Shusman 1959). These values are then inserted in the statistical relationship to have an estimate of the cycle time. Other technologies will have equivalent procedures (see Busch and Field III 1988; Han 1994; German 1998). The time required to manufacture a certain annual volume – the relevant process usage time - is then achieved by multiplying cycle time by volume.

Like before, an alternative simpler method is to establish a functional relationship between the four component characteristics described in the beginning of section 3 and cycle time. Interestingly, previous research shows that the functional form that better describes the type of
relationship between weight, complexity and cycle time for a given process also takes a generic log form (Boothroyd, Dewhurst et al. 1994, chapters 7,8,10; Kang 1998; calculations based on Veloso, Henry et al. 2000). Given this relationship, the new equation replicates (1), substituting cost by cycle time:

$$\text{Cycle Time} = A (\text{Weight})^b (\text{Complexity})^c$$

The values for parameters $A$, $b$ and $c$ are estimated by gathering information from suppliers on ranges of cycle times for different levels of complexity and weights of the components being processed and applying formulas (4) to (6), where cost is replaced by cycle time in all instances. The characteristics of the intermediate point used in the calculation, which determines the relative importance of complexity and weight and has been labeled as $\text{factor}$, is also different from before. In fact, the level of complexity and not weight is usually the critical aspect determining cycle time. So, the baseline relative importance for the factor will be 33%.

**Idle Times**

While cycle time is a critical parameter, it is important to recognize that an accurate account of how time use affects cost should also take in consideration idle time of relevant resources. Manufacturing processes are planned to respond to objectives in terms of production volume within a given period of time, typically one year. Therefore, non-operative periods of time represent a foregone opportunity to produce a certain number of components. Factors leading to idle time can be both planned and unplanned and typically include:

- **Set Up Time.** Time spent preparing equipment to run a new batch of parts.

- **Planned down time,** during which the line is attended but it is not producing, and can involve rest periods or scheduled maintenance

- **Unplanned breakdown time,** during which the line is down due to unplanned problems

These times are usually assessed by making direct inquires regarding industry practices. Values may depend on process, equipment characteristics as well firm or regional conditions.
Following the process use time logic, cycle time and idle time information can be combined to estimate \textit{Unit Fixed Cost}. For this calculation, \textit{Annual Fixed Cost (AFC)} associated with the manufacturing activity is used, as explained in section 3.1. If the equipment is solely dedicated to the manufacturing of the component under analysis, the unit cost can easily be calculated dividing the annualized cost by the annual production volume. The difficulty is that equipment is often used to manufacture different components. As a result, the appropriate unit charge should be calculated according to the relative time during which the capital equipment is used for the relevant component.

\textit{Process Time Use (PUT)} is defined as the ratio between \textit{Line Utilization Time (LUT)}, which corresponds to the amount of time needed to manufacture the required volume of components and \textit{Line Available Time (LAT)} that indicates the amount of time that the manufacturing equipment is available for operation. The later indicator is the result of company operating policies, including number of shifts, holidays and planned line down time (for aspects such as maintenance, meals or rest), as well as line and demand characteristics, that affect issues such as unplanned breakdowns and die change time, among others. For the purpose of this study, all factors leading to unproductive periods in a manufacturing plant are condensed into a \textit{Line Down} variable. The converse variable, obtained by subtracting line down from the total available time in one year defines the \textit{Line Available Time}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Figure 6: Explaining the concept of PUT (Process Time Use).}
\end{figure}

\textit{Line Utilization Time} is given by the sum of the time needed to manufacture the required volume of components, or \textit{Component Production Time (CPT)} and a burden associated with unused equipment time. The CPT usually does not take up all the line available time\footnote{It may also happen that the Component Production Time is greater than the annual available time for a given equipment. If this is the case, several lines are bought, and the Free Capacity variable represents the remainder time in the less than fully utilized equipment.}. The remaining time is \textit{Free Capacity} that can either be used to manufacture other components (\textit{Used Capacity}),

\begin{equation}
\text{PUT} = \frac{\text{LUT}}{\text{LAT}}
\end{equation}
or kept as *Idle Capacity* if no alternative use is found. If it remains unused, this *Idle Capacity (IC)* has to be charged to the components being manufactured in their relative proportion.

Figure 6 illustrates the relationship between these variables. Since CPT can be calculated by multiplying *Cycle Time* and *Annual Production Volume (Vol)*, the *Unit Fixed Cost (UFC)* can be written as:

\[
UFC = \frac{P \cdot AFC}{Vol} = \frac{LUT \cdot AFC}{LAT \cdot Vol} = \frac{Vol \cdot CT \cdot (1 + IC/(LAT - IC))}{LAT \cdot Vol} \cdot AFC
\]

\[
UFC = \frac{CT}{LAT} \left(1 + \frac{IC}{LAT - IC}\right) AFC
\]

The utilization of free capacity is important because it influences the unit cost of the component under analysis. On the one hand, if free capacity is fully utilized, then idle capacity is zero and the second term on the right hand side of equation (9) drops to zero. As a result, unit cost is only the relative share of cycle time on the overall production time available in the year. On the other hand, it is easy to see that if the idle capacity is large, the unit cost will be mostly determined by the entire line cost and not the individual component production time.

Cycle time and idle time information, together with fixed and variable investment cost calculations detailed above, provide a rather accurate estimate of the cost associated with an individual part. Moreover, since calculations are based on engineering estimates, it is possible to understand how variation in the characteristics of the part may affect manufacturing cost.

### 3.4. From Individual Technology Cost to System Cost

The previous sections describe the methods used to estimate cost of a single process technology in an individual component. Still, most anticipated cost analysis and benchmark is done at the sub-assembly level. This means that two additional critical aspects have to be considered in the System Cost Model. The first is the fact that multiple technologies may be required to complete
The processing of a particular component. The second is that individual components have often to be joined in a system through assembly. The first dimension is treated by considering multiple process steps for each individual component. For example, if the housing of an alternator requires casting and then machining, the costs for each process are calculated individually and then added to reach the total cost for processing the component. The second dimension is assembly. For this aspect, the model considers a set of fixed cost associated to equipment, building and energy, which, for a given assembly technique, is estimated following the methodology explained in the previous sections. One difference, though, is that tooling cost is not considered separately, but rather part of the equipment cost estimation.

The second difference is the calculation for cycle time. An important body of research pioneered by Boothroyd and Dewhurst (1994) has produced a set of guidelines to estimate cycle times for assembly based on part characteristics. Two critical dimensions of cycle time have been identified. The first is handling, which reflects the time required to gather and position the individual parts in place so that the joining process can be complete. This is determined mostly by part characteristics, in particular its size. The estimates for handling time using the weight variable as a proxy for size are presented in Table 2. They have been adapted from the guidelines proposed by Boothroyd and Dewhurst (1994). The second critical time in assembly is the actual joining or insertion process, which depends mostly on the process. Again, the duration estimates for the main types of processes used in auto assembly are presented in Table 3.

3 These assembly methods exclude all types of welding, that are treated as any of the other technologies described in the previous sections
Total assembly cycle time is the sum of these two components. This value is then used to estimate the use of fixed resources. It also reflects labor utilization, as these processes require worker handling. Labor costs are calculated multiplying the time needed to assemble each component and system by the unit wage cost. Total sub-assembly cost is generated by adding up individual cost contributions for each and all of the components of a system.

4. Testing the Model – Benchmarking Detail and Simplified Cost Estimation

To illustrate and validate the SCM methodology, two approaches will be followed. First, a detailed assessment for one technology is presented, comparing cost estimated through SCM with detailed process based modeling evaluations. Second, a benchmark for complete systems, involving multiple components and technologies is also considered. As a preamble, the next section discusses general modeling assumptions used in any of the estimations.

4.1. Matching Processing Conditions

The calculation of the manufacturing costs associated with the components and systems in the car rely on a set of baseline assumptions, described in Table 4. Production volume and number of years in production are instrumental in defining the type of vehicle and its useful life. These replicate what is typically found for high volume vehicles in Europe or the US. The equipment life of 10 years corresponds to what equipment manufactures and parts suppliers usually report on average, although these can vary with process. For the remaining set of variables that range from the interest rate to the average transportation time, values based on operating conditions found in the auto supply sector in a developed region. These values reflect direct information gathered from interviews with firms, or values in published sources.

Interest rate, the fourth variable in Table 4 reflects the cost of capital that suppliers in the region have to pay. The value used in the calculations, which was given by firms interviewed, was 12%. Wages of US$20 per hour are average values practiced in the autoparts sector in the region and can be gathered from industrial statistics.
Line operating conditions are defined by variables 6 to 9. The number of days of operation per year is mostly established by labor or industry contracts. A value of 240 days is usually found in the auto supplier industry. It assumes no work on weekends and two weeks of line down for personnel holidays. Two shifts correspond to having 16 hours of operation per day. The number of days of operation in one year and the number of hours of work per day establishes the baseline number of operating hours of the manufacturing processes for a year. Out of these, the line is not operating all of the time due to tasks such as maintenance and line problems. The value of 87.5% corresponds to having 2 hours of line downtime, both for planned activities and unplanned breakdowns, during the 16 hours of daily operation. Free capacity utilization indicates if capacity that is not required to manufacture the particular component considered is used or idle. The baseline assumption is that all free capacity is used.

4.2. Benchmarking Stamping Cost for individual parts

A first level of validation for the model is to make a detailed assessment of how well the SCM performs for each technology. This assessment will be illustrated for one of the key manufacturing technologies, stamping. For this evaluation, detailed data on 90 individual steel stamped parts used in an automotive body was gathered. This data involves geometry, weight and other relevant information about processing conditions, with part weight ranging from 135g to 12.7kg. The benchmark involved the calculation of individual part cost using both the SCM approach, as well as a more traditional process based cost model. In all estimations, parts with weights between 100g and 1kg are processed through a progressive die stamping technology, while those above 1kg are processed using a tandem presses. The more detailed process based model used will not be detailed here, but follows closely what is described in Kelkar (2001).
The results for the exercise are shown in Figure 7. They include cost calculations for tandem stamping, used for larger parts, as well as progressive die stamping, usually used in smaller and less complex parts. As it can be readily seen the SCM approximation is quite precise. The average difference between the two estimation procedures is less than 2% (weighted by the part weight). The results also suggest, as one might expect, that larger differences in cost are associated with more expensive parts, which results from the difficulty of approximating geometry structures with a simple complexity variable.

The approximation between costs estimated through the SCM simplification and the detailed process based assessment is also kept as total cost is broken down in its individual drivers. Figure 8 presents the results for two of the key drivers, equipment and tooling costs. In equipment, the estimates are very close, while in tooling the SCM tends to slightly underestimate the more expensive tools. Equivalent comparisons for the remaining cost drivers exist, all confirming small deviations from a more detailed cost procedure. If at all, SCM may make small underestimations of cost, which is understandable because of all the simplification in the assessment procedures.

4.3. Benchmarking Systems Cost

Contrasting to the previous section, the complete SCM methodology is now used to estimate costs for a diverse set of complete vehicle subassemblies. Table 5 provides five examples of such sub-assemblies for which it was possible to find industry cost quotes. As it can be seen, the systems have a wide variety in the number of individual components and technologies, ranging from stamping to injection molding, non-woven preparation or casting. For these, the costs generated through SCM estimates fall within a 20% difference in cost from the OEM quotes.
These results are important because one needs to ensure that cost evaluations generated through SCM are sufficiently accurate and display no systematic errors. The range of differences at the sub-assembly level between SCM estimates and external quotes provides a good indication of the validity of the modeling method. In fact, it is important to reaffirm that a close fit between individual sourcing cost and SCM estimates is not expected, or even an objective that should be pursued. The actual price that an OEM pays for a particular subassembly depends on a large number of aspects, that range from the particular location of the plant and the supplier of the component, the exact volume of production and whether there are wider purchasing agreements that go beyond the individual sub-assembly. Instead, SCM results will provide what one may expect as the average cost of a given system produced under a set of manufacturing conditions.

A potential problem, given the simplifications of the SCM estimation process, would be an underestimation of cost. Although benchmark errors in estimation displayed in Table 5 show evidence of both values where the external quote is above and below the value estimated through SCM, one does observe a slight tendency to have cost estimations below outside values – the same tendency can be observed in the stamping benchmark evaluation. Nevertheless, this effect did not seem to be very discernible.

5. Conclusions

This paper proposes a methodology to evaluate the cost of complex systems with a large number of individual components and subsystems. First it describes the existing techniques for estimating cost and their relative advantages and disadvantages. Then it describes a new method called Systems Cost Modeling (SCM). SCM proposes a number of simplifications in the estimation process, when compared to existing methods, which enable building bottom-up cost structures, estimating cost at the level of the individual component and aggregating it to the subsystems and system level. The main advantage of this SCM is that it requires relatively few inputs per part making the task of estimating cost of large numbers of parts more manageable.
The work also shows the validity and application of the SCM methodology using two complementary approaches. First, a detailed assessment for stamping is shown, comparing cost estimated through SCM with detailed process based modeling evaluations. Second, a benchmark for complete systems, involving multiple components and technologies is considered. The results show how that the model has fairly good prediction capabilities, with small deviation from detailed cost estimates and industry cost quotes.

This methodology has a very wide array of applications (see Veloso 2001 for a discussion), from early estimation of cost implication of different design approaches in a complex system (e.g. steel vs. aluminum), to supply chain location analysis, or policy implications associated to supply chain structures, such as local content requirements.

6. References


Figure 1: Estimating Component Manufacturing Cost Through SCM

![Diagram of Component Manufacturing Cost Estimation]

- **VARIABLE COSTS**
  - Material Cost
  - Energy Cost
  - Labor Cost
  - Logistics Cost

- **FIXED COSTS**
  - Equipment Cost
  - Tool Cost
  - Building Cost
  - Fixed Overhead

- **LOCAL FACTOR PRICES**

Figure 2: Equipment Cost Estimation Techniques for Technical Cost Modeling

![Diagram of Equipment Cost Estimation]

- **Component (e.g. Engine Block)**
  - Material
  - Area
  - Volume
  - Shape

- **Equipment Key Characteristic**: Engineering Estimation
- **Regression Estimation**: Equipment Cost
Table 1: Generic Functional Relationship Between Weight, Equipment Key Characteristic and Cost

<table>
<thead>
<tr>
<th>Process</th>
<th>Weight</th>
<th>Key Charact</th>
<th>Eq. Cost</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injec. Molding</td>
<td>Logarithmic</td>
<td>Clamp Force</td>
<td>Linear</td>
<td>(1)</td>
</tr>
<tr>
<td>Die Casting</td>
<td>Logarithmic</td>
<td>Clamp Force</td>
<td>Linear</td>
<td>(2)</td>
</tr>
<tr>
<td>Stamping</td>
<td>Linear</td>
<td>Press Force</td>
<td>Logarithmic</td>
<td>(3)</td>
</tr>
<tr>
<td>Machining</td>
<td>Linear to Logarithmic</td>
<td></td>
<td></td>
<td>(4)</td>
</tr>
</tbody>
</table>

Sources: Own calculations based on (1) Boothroyd, 1994, Chapter 8; (2) Chapter 10; (4) Chapter 7; (3) Han, 1994.
Figure 4: Three Point Estimation of Equipment Cost

Figure 5: Three Point Estimation of Tool Cost
Figure 6: Critical Relationships in Line Utilization

Table 2: Handling Time for Components (adapted from Boothroyd, Dewhurst et al. 1994)

<table>
<thead>
<tr>
<th>Weight</th>
<th>W &lt; 10g</th>
<th>10g &lt; W &lt; 50g</th>
<th>50g &lt; W &lt; 5000g</th>
<th>W &gt; 5000g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling time</td>
<td>8 sec</td>
<td>5 sec.</td>
<td>2 sec.</td>
<td>15 sec.</td>
</tr>
</tbody>
</table>

Table 3: Time required for Joining Processes (adapted from Boothroyd, Dewhurst et al. 1994)

<table>
<thead>
<tr>
<th>Joining Process</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layed Fit Press Fit</td>
<td>3 sec</td>
</tr>
<tr>
<td>Adhesive Snap Fits</td>
<td>5 sec</td>
</tr>
<tr>
<td>Spring Release Clips</td>
<td></td>
</tr>
<tr>
<td>Clamp</td>
<td></td>
</tr>
<tr>
<td>Stitching Rings</td>
<td></td>
</tr>
<tr>
<td>Heat Pins</td>
<td></td>
</tr>
<tr>
<td>Screw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 sec</td>
</tr>
</tbody>
</table>
Table 4: Assumptions Used in System Cost Model Estimations

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Annual Production Volume</td>
<td>200,000</td>
</tr>
<tr>
<td>2. Years of Production</td>
<td>5</td>
</tr>
<tr>
<td>3. Life of Equipment</td>
<td>10</td>
</tr>
<tr>
<td>4. Interest Rate</td>
<td>12%</td>
</tr>
<tr>
<td>5. Wage ($/hour including benefits)</td>
<td>$20</td>
</tr>
<tr>
<td>6. Days per Year</td>
<td>240</td>
</tr>
<tr>
<td>7. Number of Shifts</td>
<td>2</td>
</tr>
<tr>
<td>8. Line Available Time</td>
<td>87.5%</td>
</tr>
<tr>
<td>9. Free Capacity Utilization</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 7: SCM vs. Process Based Model - Benchmark Total Costs
Figure 8: Equipment Cost Benchmark and Tooling Cost Benchmark

![Graphs showing cost benchmarks with different markers for SCM prog, SCM tand, and TCM.]

Table 5: Examples of Sub-Assembly Cost - SCM Estimate and Data Provided by OEM

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Components</th>
<th>Number of Technologies</th>
<th>SCM Estimate</th>
<th>Industry Quote*</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Left Seat</td>
<td>35</td>
<td>8</td>
<td>$79</td>
<td>$85</td>
<td>8%</td>
</tr>
<tr>
<td>Steering Wheel</td>
<td>13</td>
<td>10</td>
<td>$10</td>
<td>$11</td>
<td>10%</td>
</tr>
<tr>
<td>Front Caliper Left</td>
<td>12</td>
<td>5</td>
<td>$28</td>
<td>$24</td>
<td>-14%</td>
</tr>
<tr>
<td>Starter#</td>
<td>21</td>
<td>9</td>
<td>$30</td>
<td>$35</td>
<td>17%</td>
</tr>
<tr>
<td>Steering Column#</td>
<td>71</td>
<td>8</td>
<td>$60</td>
<td>$48</td>
<td>-20%</td>
</tr>
</tbody>
</table>

*quote is for very similar component, but not exactly the same one

# It is important to note that the SCM does not estimate costs for electronics – these are taken from information on average prices by vendors and clients.