Using Bottoms-Up Cost Estimating Relationships in a Parametric Cost Estimation System

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Abstract

The parametric approach to manufacturing cost estimation is preferred in many situations because a limited amount of part data is required to generate an estimate. However, the limited data means that the estimate cannot achieve the accuracy of a bottoms-up estimating system.

A hybrid cost-estimating system has been developed and implemented to estimate the cost of jet engine components. The system utilizes a bottoms-up estimating approach for the actual cost estimates, but appears as a parametric system to the user. The inputs needed for bottoms-up cost-estimating relationships (CERs) are calculated from user-specified parameters based on relationships derived between part parameters and feature attributes.

Keywords: Cost Estimation, Attribute Estimating Relationships

1. Introduction

A variety of approaches have been developed for generating models to estimate the cost of manufactured products. Duverlie & Castelain [3] identified four basic categories of estimating methodologies:

- Intuitive
- Analogical
- Parametric
- Analytical

Methods in the first two categories on this list are more limited in their applicability. The intuitive method requires an expert (or an expert system) that can generate an estimate of the cost. This may not exist for many situations and the applicability is limited by the experience of the expert. The analogical method can be used when a new product is similar to an existing product. Duverlie and Castelain note that this method is best used with group technology, when similarities between parts can be quantified.

The other two methods on the list are more broadly applicable. Both the parametric and analytical (referred to as bottoms-up in the remainder of this paper) methods estimate cost as a function of parameters of the product. Parametric methods are high-level, with cost estimated from overall part parameters, while bottoms-up methods are detailed, estimating cost for each feature on a part.

In the parametric method, Cost-Estimating Relationships (CERs) are developed by determining a relationship between the values of the significant attributes of a group of parts and their known costs. Typically, regression is used to create a CER that relates a part's cost and its attributes, although Günaydin and Doğan described an approach using a neural network to determine the relationship [4].

Parametric cost estimation is well-suited to the preliminary design phase, as it estimates cost based on a limited number of attributes, but because less information is used, it is less accurate. Also, because the information that is used is typically part parameters rather than feature parameters, it can be difficult for design engineers to identify *why* design changes are affecting the cost, even if the parametric CERs are accurately describing *how much* the changes are affecting the cost. The estimated cost is not broken down by feature, so it can be difficult to identify the true cost drivers.

In addition, parametric CERs can be prone to generating large errors when the size of parts changes (i.e., CERs generated using large parts may not be scalable for estimating the cost of small parts). Also, when new processes are implemented, the CERs cannot be reused and must be recalculated, since the change in cost due to the new process cannot be adjusted individually.

The bottoms-up method uses CERs that attempt to estimate the time to perform the manufacturing processes that create the features on a part. This allows greater accuracy in the estimate, but it also requires much more information, which may not be known early in the design process.

In developing a bottoms-up cost estimation system, each process or operation that contributes to the final cost of a product should be accounted for with its own CER that estimates the time or cost to perform that process. Often, machining CERs are based on the material removal rate for the process. For example, a product that requires drilling would have a CER to estimate the time to drill a hole that may be based on factors such as the diameter of the hole, the depth of the hole, and the feed rate. Ben-Arieh [1] and Ben-Arieh and Li [2] described systems for cost estimation of rotational parts that calculated turning time from the amount of material to be removed and the material removal rate.

In addition to its accuracy, another advantage of the bottoms-up estimation method is its transparency: all of the processes that contribute to a part's cost can be accounted for and the amount that each feature adds to the total estimated cost can be determined. This provides greater insight for designers about how their decisions affect cost and how they can minimize the production cost of a part as it is being designed. Also, bottoms-up CERs are general, so CERs developed for one type of part can be applied on another type of part with minimal changes. For example, once a CER to estimate the time required to drill a hole has been developed, the CER can be applied on new types of parts that also require drilling.

The main drawback of the bottoms-up method is that it can be very time consuming to develop all of the necessary CERs. To create a true bottoms-up estimate, a manufacturing engineer is needed who can perform the process planning on the part being designed and translate the design into processes—this is not something that is done by the design engineer. Even when developing a generalized bottoms-up system, a manufacturing engineer is needed to determine the processes that would be used for individual features and the time to manufacture the features.

In addition, it can be time consuming to generate the cost estimate in a bottoms-up system because of all of the attributes that are needed. Many of the attributes may even not be settled in the preliminary design stage, leaving the designers to guess at values or ignore those attributes, both of which can have a negative impact on the accuracy of the cost estimate.

2. Project Overview

The motivation of this research project was to improve the system used by a jet engine manufacturer to estimate the cost of engine components. Their original system was parametric, which provided satisfactory accuracy in estimating the cost of an entire engine, but was less accurate for the individual part.

Initially, because the project objective was to improve accuracy, a complete bottoms-up approach was used. However, after models had been developed for a limited number of part families, it was determined that this approach would not be feasible as a long-term solution. Because the number of attributes required to model a part, it would be too time-consuming for a user to generate a cost estimate.

Therefore, the methodology was revised to reduce the number of attributes needed to generate a cost estimate. The bottoms-up CERs were retained, to maintain the accuracy of the original methodology, and Attribute Estimating Relationships (AERs) were used to estimate some of the attributes required as inputs to CERs. The concept of AERs was originally discussed in [6]. This paper reviews some of the basic information about AERs and provides additional details about their use, but additional details are available in the original paper.

3. Methodology

3.1. Cost Estimating Relationships

When developing the bottoms-up CERs for the original methodology, standard material removal formulas were tested using actual part dimensions. These formulas were compared to known feature machining times and adjusted by scaling to produce the final CER. The scaling was intended to account for variations between the "handbook" parameters and the actual ones being used.

An example of a feature CER is shown in Equation (1):

$$time_{hob} = k(N \cdot L) \tag{1}$$

This CER estimates the time to form a spline by hobbing, where N and L are the number of teeth and length of the spline, respectively. The variable k represents a constant that combines the parameters of the hobbing process, such as cutter diameter, cutting speed, and feed rate. CERs were developed to estimate the time to create a wide variety of features found on jet engine components, including slots, holes, and seal teeth.

In the revised methodology, a similar approach was used to generate CERs, again producing formulas of the same form as Equation (1). The only modification to the approach was that handbook parameters were not used in the CERs before scaling. Instead, scaling alone was used to determine the relationship between the feature dimensions and the processing time. This was done because the final CER produced has a single coefficient, so the individual machining parameters are not included individually in the formula. In addition, handbook parameters are not available for the non-traditional processes that are used on some features.

It might be tempting to take this approach a step further and develop the CERs with respect to the part dimensions, rather than feature dimensions. That is, since

time = *f*(*feature dimensions*)

and

feature dimensions = *f*(*part dimensions*)

one might be inclined to develop CERs as

time = *f*(*part dimensions*)

However, this was not done for two reasons. First, it limits the reusability of the CERs. If a CER is developed as a function of a part dimension, it cannot be adapted to a new part that doesn't have the same dimension. Also, it limits the transparency of the system. The user may see that the cost increases significantly as a given dimension increases slightly, but it may not be apparent what (other than the added material) caused the cost to jump.

3.2. Attribute Estimating Relationships

Essentially, Attribute Estimating Relationships (AERs) are capturing design requirements or design preferences that are used explicitly or implicitly by the designers. However, a design engineer does not need to specify these relationships; instead, they are derived mathematically from part and feature dimensions of existing parts as seen on a CAD model.

Examples of AERs that might be identified are shown in Table 1. By definition, the inside diameter (ID) of a part or feature is going to be smaller than its outside diameter (OD). The exact relationship is derived by studying previously designed parts.

Table 1: Examples of AERs

Relationship	Interpretation
ID = OD – 0.75	The ID is 0.75" smaller than the OD
ID = 0.95 · OD	The ID is 95% of the OD
ID = 0.98 · OD – 0.13	The ID is 0.13" smaller than 98% of the OD

With the AER, the user only needs to specify one value (the OD) and two values (OD and ID) are available to be used in the CERs.

Attributes are typically dimensions of the part being evaluated, but they can also be used to capture other important descriptive information. Other types of attributes that may be used include:

- Boolean attributes (Yes/No)
- List attributes
- Quantity attributes

An attribute may ask whether a particular feature appears on the part being modeled (Boolean) or it may have a list of options for the configuration or function of the feature. Then, depending on the choice that is made, different AERs can be used to determine the values to be used in the CERs.

Quantity attributes can be used to indicate how many instances of a feature appear on the part, such as the number of sets of threads. Then, the dimensions of each feature can be generated from AERs, using other part attributes or using user-specified attributes that apply only to that feature, and which are needed only when the quantity is greater than zero.

4. Results

4.1. Using AERs for Part Features

Koonce, et al. [5] described a hierarchical cost-estimation tool that allowed the implementation of a bottoms-up cost-estimation method. The tool was used to implement CERs for estimating the cost for components of a jet engine. This bottoms-up method produced more accurate estimates than the parametric method that had been used previously, with an average improvement of 22% over previous estimates, based on modeling of 80 parts from three different part families.

This project uses the same cost-estimation tool used by Koonce, et al. To evaluate the impact of using AERs to replace user-specified inputs, AERs were derived for most of the features found in a family. The general form of the AER formula is shown in Equation 2, where y is the attribute to be estimated; x_i are the values of the dimensions of the part; and β_i are the coefficients.

$$y = \beta_0 + \beta_1 x_1 + ... + \beta_n x_n \qquad (2)$$

All of the part attributes that were believed to be related to the attribute to be estimated were included in the initial formulation, to assess which attributes had the strongest relationship. However, it is also desirable to maintain the simplicity of the AERs, so input attributes with a weak relationship were dropped from the AER.

For each instance of a feature, the appropriate x_i values can be collected, producing z instances of Equation 2 (from z instances of the feature). From these equations, the values of β_i can be calculated to minimize the error. The objective in solving for the β_i values is to minimize the standard deviation of the percent error of the estimates, while keeping the average error at 0%.

Minimizing the standard deviation keeps the positive and negative errors from canceling each other out; setting the average error at 0% keeps the AER centered on the actual values. A traditional least-squares regression method is not used because that would give much higher weight to high-cost parts than low-cost parts, since even a small percent error on a high-cost part would be a large absolute error. Considering the percent error instead of absolute error gives equal weight to high-cost and low-cost parts.

This procedure for generating AERs for feature attributes was tested on jet engine disks, with formulas derived to calculate the quantities and dimensions for the relevant features. A comparison of the estimates generated for the number of dovetail slots on a disk and the actual number of dovetail slots is shown in Figure 1. The straight line represents a perfect estimate, which is generated by plotting the actual quantity vs. the actual quantity.

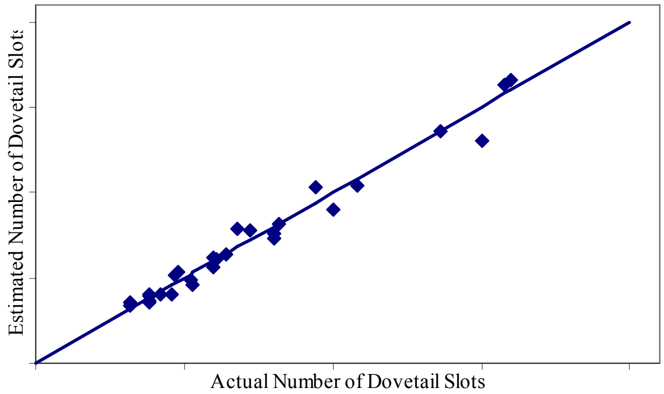

Figure 1: Comparison of Actual Number of Dovetail Slots vs. Estimated Number of Dovetail Slots

This figure shows that the number of dovetail slots can be estimated accurately throughout the range of possible values, from the lowest values to the highest values. Therefore, the user does not need to specify the quantity, which is a necessary input for the CER that calculates the time to form those slots; instead the values can be calculated based on the average diameter and width of the rim that the slots are located on.

AERs were developed for most of features that are found on jet engine disks. Using the AERs, the cost estimates were recalculated and the performance of the AERs was compared to the accuracy of the estimates with full feature information. The average percent error was the same for the detailed cost estimates and the cost estimates with AERs.

The standard deviation of the percent error (a measure of how far the estimates vary above and below the actual cost) for the AER cost estimates increased by only 3% over the cost estimates with detailed feature information. This indicates that there were some estimates that were further (high or low) from the actual cost, but the size of this shift was not significant when AERs were used to calculate the feature quantities and dimensions.

In this testing, AERs were used to calculate values for more than 30 different inputs to the feature CERs that are used on disks. Some of these features (e.g., flange holes) may appear in multiple locations on a part, so more than 30 additional attributes may potentially be needed to fully describe all of the features on a disk.

In this testing, only linear functions were tested for use as AERs, although the same procedure could be used to generate non-linear AERs if necessary. For example, an AER to estimate an area parameter that is used in a process (e.g., shot peening) might be better estimated as $f(x_i^2)$ instead of $f(x_i)$.

4.2. Using AERs for Part Geometry

In the models developed by Koonce, et al. [5], a significant number of attributes were needed to describe the overall geometry of a part. This geometry is important because it determines the part volume, which affects the amount of material to be purchased and hence the material cost. The part volume also affects the amount of material to be removed, both through the original rough turning and through additional machining processes.

To simplify the process of specifying attributes to create the geometric models, the use of AERs was again examined. In addition to using AERs to estimate the dimensions of a part's features, they can also be used to estimate geometric attributes of a part.

Figure 2 shows the geometric attributes of a basic jet engine disk. The illustration shows the cross-section of the disk; the full part is generated by revolving the cross-section 360° around the centerline shown at the bottom of the figure.

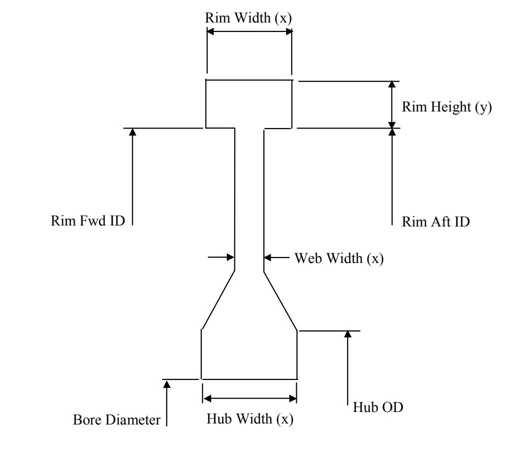

Figure 2: Basic Geometry of a Jet Engine Disk

The cross-sectional shape for a part (from which the part volume could be calculated) can be estimated without requiring the user to specify all of dimensions labeled in the figure. This can be accomplished by using AERs to estimate some of the dimensions, using the same form shown in Equation 2. As necessary, a list attribute can be used to classify the parts based on their general shape, which indicates the geometric attributes that need to be estimated on the part.

For disks with a cross-section similar to that shown in Figure 2, only four input parameters were needed to obtain a very good estimate (average error = -3.5%) of the forging volume estimated from detailed attributes: hub width, minimum ID, maximum OD, and web geometry. The web geometry attribute was a list attribute that was used to indicate the presence of web holes because having these holes affects the web thickness.

The effectiveness of this combination of attributes at estimating the forging volume agrees with the geometry of forging. The boundaries of the overall part can be defined by a maximum OD, a minimum ID, and a width and these boundaries must be covered by the forging.

For parts with appendages, the approach of selecting attributes to define the overall boundaries of the part again produced good results. Testing determined that a good estimate of the volume could be obtained from three attributes: maximum OD, minimum ID, and overall length. Although many of the parts in this classification only had one appendage, all parts were assumed to have two appendages, as well as flanges extending from the end of each appendage toward the centerline of the part. This eliminated the need for an attribute to identify the number of appendages or the type of flange and did not affect the quality of the estimates. In calculating the part volume using AERs instead of all of the part's geometric attributes, the average error between the part volume in the detailed estimate and in the AER-generated estimate was 1.7%.

5. Conclusions

This paper has discussed how Attribute Estimating Relationships can be used to simplify a bottoms-up cost estimation system so that is appears more parametric to the user. This has the advantage of reducing the time required to generate a cost estimate, while retaining the transparency and most of the accuracy of the complete bottoms-up system. AERs also eliminate the need to determine detailed feature dimension in the preliminary design phase, when such information is often not available.

AERs can also be used to calculate the dimensions of geometric attributes of a part. This again limits the amount of information that is needed to calculate the cost estimate while still allowing generation of a detailed geometry. This can be applied to parts in a family that share a similar structure, allowing a complex cross-sectional shape to be formed by following consistent rules for how to combine the actual and estimated dimensions into a finished shape.

Over the course of this research project, the approach described in Section 3 has been applied to develop cost models for the majority of part families in a jet engine. The ability to reuse CERs has been a significant advantage in reducing the time to program and implement new cost models. AERs have been used for all families that have been studied, for both feature attributes and geometric attributes. For almost all parts that have been modeled, the cost estimate changes by less than 5% from the detailed cost estimate, which demonstrates the reliability of the AER approach.

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