Adapting Bottoms-up Cost Estimating Relationships to New Systems

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ABSTRACT

Cost-estimation can be performed using high-level parametric estimates, or with a bottoms-up approach using process-based cost estimation. Although it can be more difficult to develop, the bottoms-up approach offers many advantages, including the ability to reuse the cost estimating relationships (CERs) on new parts. This paper discusses the process of adapting a methodology that utilizes process-based CERs that were developed for estimating the cost of jet engine parts to create a system to estimate the cost of gas turbine parts. Issues that arose are described, along with the strategies used in resolving them.

1 INTRODUCTION

Taking a process-based approach to estimating the cost of a product or system provides a number of advantages. With cost estimating relationships (CERs) that estimate the cost of the processes that are required to produce the features on a part, rather than a parametric CER that estimates the overall part cost directly, cost estimates can be tied to those specific part features. This provides information that is more useful to designers who are trying to identify opportunities to reduce the manufacturing cost of a design.

Also, because the estimated cost of a process is directly tied to the labor hours to perform the process, it can be more accurately calibrated to represent a "should cost" estimate for the part. Parametric CERs are typically derived from historical cost data, so they are more likely to represent what the part "does cost", which may be higher than what it should cost.

Another advantage of process-based cost estimation is that a CER to estimate process cost can be reused for different part types where the same process is used. Unlike parametric CERs, which are applicable only to parts that share the characteristics of the parts that were used to generate the CER, process-based CERs are transferrable to new part types, or even to new systems.

In transferring the CERs to new part types, it is important to consider the applicability of the CERs to the new parts. Process-based CERs are essentially parametric CERs at the process level instead of the part level, so they have the same limitations. For example, as noted above for parametric CERs, process-based CERs are only applicable when the processes that are being evaluated share the characteristics of the processes that the original CER was based on. If the process changes, the original CER needs to be recalibrated or replaced. The change in process maybe due to an entirely new process being used (such as shifting from investment casting to sand casting) or it can be due to a change in equipment that is feasible for the new parts (such as shifting to a lathe with a larger horsepower).

The work discussed in this paper originated from a process-based methodology that was developed to estimate the cost of jet engine components [1]. Once the methodology had been successfully applied to most of the parts found in a typical jet engine, the methodology was adapted for estimating the cost of gas turbines that are used in power generation. The advantage of this transition is that gas turbine architecture is very similar to that of a jet engine. This made it possible to reuse many of the geometric models and CERs that were originally developed for jet engine components.

The general approach of the cost estimation methodology is illustrated in Figure 1.

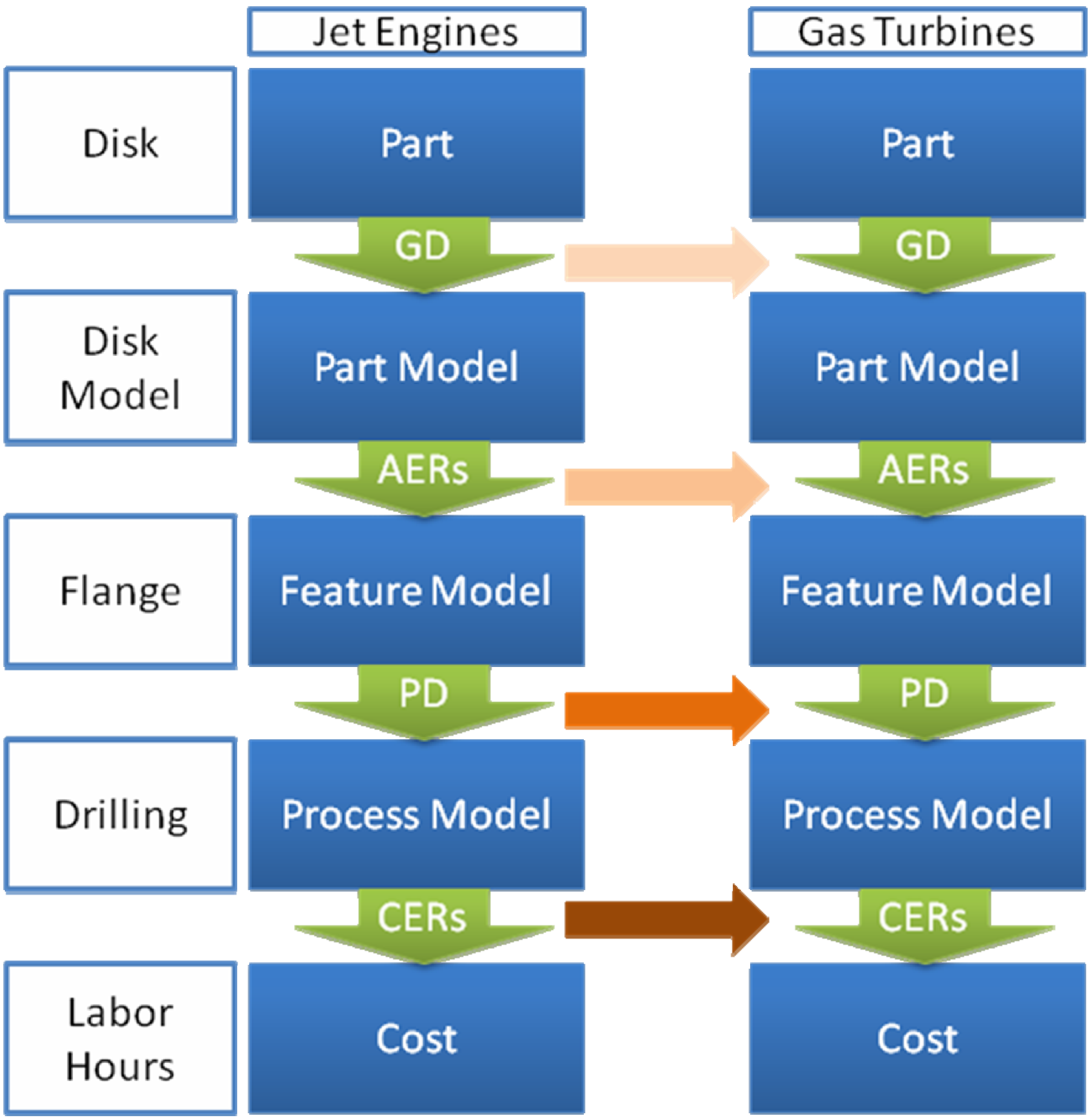

Figure 1: Illustration of cost estimation methodology

Starting with a given part type to be modeled, the attributes describing the part are converted to a model using Geometry Definitions (GD). Then the part-level attributes are used to calculate the values of feature attributes using Attribute Estimating Relationships (AERs). Then, for each feature, the feature attributes are used to determine the operating parameters for the relevant process(es) based on the Process Definitions (PD). Finally, the CERs are used to calculate the cost of performing the process. Additional details about the application of this methodology are provided in Section 2.

After the methodology was developed for jet engines, it was used as the starting point for a cost estimation methodology for gas turbines. At the most detailed level of the hierarchy, many of the CERs could be directly used, since they describe a process and in many cases the identical process is used even though the part type is different. At the top of the hierarchy, some of the Geometric Definitions could also be reused, since there are similarities in the geometry of the parts; however, less of this information could be reused, since the geometries are not exactly identical.

Because the approach to cost estimation was already developed and many of the CERs already existed, the development time that was needed to develop the gas turbine cost estimation methodology was approximately one quarter of the time that was required to develop the original jet engine methodology.

This significant reduction in development time demonstrates one of the advantages of a process-based approach to cost estimation. In addition, the existence of the jet engine methodology also facilitated development in areas where little or no cost data existed for gas turbines. Without the ability to use CERs derived for jet engine data, it would have been difficult to create CERs for features on gas turbines for which data were not available.

In spite of the benefits of utilizing process-based CERs, there were situations in which they could not be directly transferred from the jet engine cost models to the gas turbine cost models. The remainder of this paper describes the cost estimation methodology that was used for jet engines, as well as issues that arose in adapting the methodology for application to gas turbines, and how the issues were resolved.

2 OVERVIEW OF COST ESTIMATION METHODOLOGY

For several years, Ohio University has been engaged in research to develop improved cost estimating procedures for jet engine components. The resulting methodology uses process-based CERs to provide a bottoms-up approach to estimate the cost of a given part design. The cost estimate for manufacturing the part is determined by accumulating the estimated cost each of the manufacturing processes needed to create the features on the part.

However, directly using the process-based CERs would make it very time-consuming for users to generate a cost estimate, since each CER has its own attributes (e.g., feature dimensions) that are used to estimate the process cost. In addition, it would be very difficult to utilize a process-based system early in the design process for a new part or system, when only limited information about the part design is available, and this information is mainly related to the overall part geometry and not the design of the features to be produced.

To overcome these difficulties, the process-based CERs were implemented within a parametric framework [1]. This means that most of the user-entered attributes are high-level descriptions of part geometry and these attributes are used to map appropriate values to the feature-level CERs. The user-entered attributes are generally related to the geometry of the part, since getting an accurate description of the general part geometry is important for estimating the cost of the material and the forming process (e.g., casting, forging).

The mapping process is performed using attribute estimating relationships (AERs) [1] that calculate the value of the attributes that are needed as inputs to the process CERs by utilizing the user-specified attributes. To illustrate the function of AERs in the cost estimation methodology, consider a flange that is located on a given part. The cost estimate for the flange would require a CER to calculate the cost of drilling the holes in the flange, and the inputs required for a process-based drilling CER would include the diameter of the holes, the depth of the holes and the number of holes. Each of these CER attributes would utilize a different type of AER to determine the value.

For the hole diameter, a constant value would be used, since this attribute is not a significant cost driver:

$$diameter = c \tag{1}$$

The depth of the hole could be set equal to the flange thickness, which may be specified by the user to describe the overall part geometry:

$$depth = flange\ thickness \tag{2}$$

Since the hole will need to be drilled entirely through the flange, the flange thickness and the hole depth must be equal. By using the AER approach to set the hole depth, this eliminates the need for the user to specify redundant information, and it also prevents inconsistencies from arising, if the user were to change one of the values and not the other.

The number of holes could be calculated as a linear function of the flange diameter:

$$quantity = k \cdot flange\ OD + c \tag{3}$$

The values for k and c in the AER would be derived from finding the best-fit line between the CER attribute (e.g., *quantity*) and the relevant part attribute (e.g., *flange OD*). This relationship reflects the fact that as a flange gets bigger (i.e., its outside diameter increases), the number of holes on the flange will also increase. The relationship would approximate the design practice, in terms of how the part design drives the design of features.

The attributes which are calculated in Equations (1)-(3) using AERs would then be inputs to the process CER. In general, each process CER is based on the operating rate of the process, such as the material removal rate of a machining process. The process CERs consider the physics of the manufacturing process being performed, so that they can be applied wherever the process is performed and aren't applicable to only one part type.

AERs can also be used at the system level to map from attributes that describe the overall assembly down to attributes that describe the components of an assembly [2]. Then, from the estimated component attributes, the feature attributes can be estimated for each component. This allows process-based CERs to still be used in generating the cost estimates at the feature level, while only requiring the user to specify attributes at the system or assembly level.

To implement this cost estimation approach, the FIPER cost estimation tool [3] was used, since it supports the use of process-based CERs as well as the mapping of attribute values between levels of the part, as shown in Figure 1.

3 ISSUES OBSERVED

In adapting the cost models developed for jet engines for use in gas turbines, different issues were encountered. This section describes some of the lessons learned from dealing with these issues, and strategies that were used to resolve them.

3.1 Process Changes

It is important to remember that the CERs which calculate the costs are process-based and not feature-based. This means that a new CER is needed when there are changes to the manufacturing processes being used, even if the feature appears to be the same. For example, large holes may be made by drilling, but small holes may need to be formed using Electrical Discharge Machining (EDM). The physics of each of these processes are different, so they would have different CERs.

A CER may also need to be changed if the equipment used to perform the process is changed. Figure 2 shows an example of the relationship between part size and cost for a low horsepower machine and a high horsepower machine.

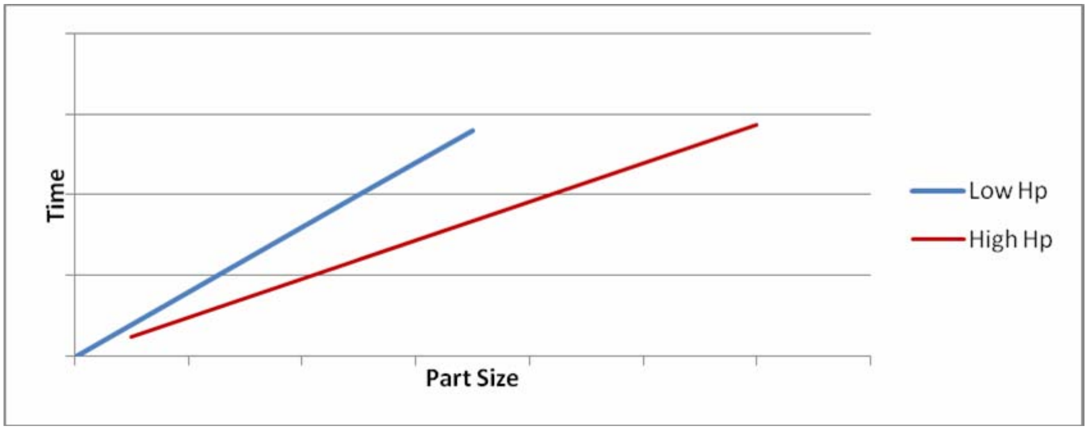

Figure 2: Relationship between processing time and part size

The high horsepower machine is capable of removing material more quickly, so it has a lower slope, which would require a different CER. However, small parts would not but manufactured on a large machine, so it is important to determine which machine (and therefore, which CER) should be used in a given situation.

Accounting for these changes is a two-stage process. First, it is necessary to recognize when the process has changed. Design engineers may not know which process is being used, so it is important to include process engineers in the development process, to help in determining which processes (and their associated CERs) are still applicable, and what new processes are being used.

Once the processes which need new CERs have been identified, the development process is straightforward. Manufacturing times are used (or in the absence of manufacturing times, manufacturing costs) and a relationship between the time (or cost) and the relevant process parameters can be determined.

3.2 Changes in Geometric Relationships

Changes in the geometry need to be addressed in two ways. First, the overall part geometry needs to be considered. This geometry drives the overall material cost, as well other aspects of the cost, so it is important that the part model accurately reflect the part geometry. Second, as with the CERs, AERs will also need to be recalibrated. Since AERs reflect the relationships between feature geometry and overall part geometry that are driven by the design practice, the AERs need to be updated to reflect the fact that design practice is likely to change when products for a new application are being designed.

Based on the experience of developing a cost estimation methodology for gas turbines, most of the attributes that describe the geometry of parts in a given family for one product type can be used to describe the geometry for parts that perform the same function in another product type. The product designs are not identical, so the part models need to be updated to account for geometric features that have been changed or added. But in most part types, the geometric models for jet engine parts were used as a starting point for developing the corresponding geometric models in gas turbines. This reduced the time required to develop the model as well as the time to program the completed model, which was one of the factors that allowed the gas turbine cost models to be developed more quickly than the jet engine models.

AERs were also recalculated for the gas turbine models. AERs of the form shown in Equation (2) (where the feature attribute is equal to a part attribute) generally did not require changes. However, AERs of the forms shown in Equations (1) and (3) did need to be reviewed. When a constant value was used (as in Equation (1)), the value often needed to be increased to reflect the increased size of features on gas turbine components. AERs that were derived by scaling from the part geometry (as in Equation (3)) were also reviewed to account for differences in design practice between jet engine components and gas turbine components.

3.3 Changes in Production Rate

One new issue that was encountered with the development of the gas turbine cost estimation methodology was that the production rate of the gas turbines was significantly lower than the production rate of most jet engines that were studied. This led to situations where there was a difference between what a part should cost (when using a physics-based approach to estimate the time to perform the manufacturing processes) and the actual lowest cost that the part could be purchased for.

If the cost estimation methodology is being used solely to compare the relative cost of different design options and if the “market escalation factor” is the same for all manufacturing processes that are required to produce a part, then the escalation factor can be ignored—the estimated costs for all designs will be escalated by the same factor and the relative cost of each design will not change.

However, these assumptions do not necessarily hold true in many cases. The cost estimates are used not only to make decisions between designs, but they are often interpreted as being costs that will be attained when suppliers are being chosen. In addition, the escalation doesn’t typically apply equally to all processes, particularly when some processes are performed by suppliers and some are performed in-house.

To account for the existence of market-based escalation, a scaling factor was incorporated into the models. The magnitude of this factor in different cases was based on historical cost data, to reflect the increase in cost for situations in which vendor options were limited. The application of this factor was turned on by a user-specified attribute, so that the user has the option of removing the factor to see what the part should cost if market escalation did not affect the part. This allows the system to provide an estimate of how much will be paid for the part, so that designers have reasonable expectations of the outcome of purchasing decisions.

4 CONCLUSIONS

The process of adapting a cost estimation system for jet engine components for use in estimating the cost of gas turbine components has demonstrated the benefits of using a process-based approach to cost estimation. By reusing geometric models from similar components in other systems, the geometric models of new parts can be created more quickly. And reusing CERs speeds the development process, particularly when there is limited data available for creating new CERs.

In this case, the gas turbine cost estimation system was developed in approximately 25% of the time that was required for developing the system for jet engine cost estimation. This faster development was not achieved at the expense of the accuracy of the estimates. The accuracy of the cost estimation system for both product lines was similar.

Having common CERs and similar geometric relationships between the two systems also provided benefits for the jet engine cost estimation system. Some of the methods developed for gas turbines were applied back to the jet engine system, to improve its estimates for the cost of new processes. Going forward, as further development is undertaken to improve the capabilities of both systems, improvements in one system can easily be implemented in the other system, to expand the impact of the investments made in enhancing the cost estimation methodology.

However, as was observed in this process, care should be taken when reusing the process CERs and AERs to verify that they are still applicable to the new system being modeled. In some cases, the formula for the CER may need to be recalculated, or a new CER may be needed if a different process is used to manufacture the feature.

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