MANUFACTURING EVALUATION OF DESIGNS: A KNOWLEDGE-BASED APPROACH

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ABSTRACT

Manufacturing evaluation is performed with heuristics that are developed internally by the manufacturing experts in the company. Many of the existing manufacturing evaluation systems rely on highly specialized knowledge, extensive databases, and require a significant amount of time and cost that make these tools in general unavailable early in design and to small manufacturers who do not have this expertise. Oftentimes, the level of detail is unnecessarily precise. Useful results can be obtained at a more abstract level without the exact data required by existing systems. This research project is concerned with the modeling of the manufacturing capability process information and knowledge to support manufacturability evaluation of designs.

Keywords: Classification, manufacturability evaluation, knowledge-base, fuzzy rules.

INTRODUCTION

Manufacturability evaluation of design is regarded as an important element of performing concurrent engineering. An early assessment of the product manufacturability issues has the potential of reducing the overall time-to-market by reducing the number of design changes [Boothroyd, 1994]. Furthermore, it is indicated that upwards of 70% of a product's cost is determined during the preliminary design stages [Ullman, 1992]. Although the benefits of early manufacturing evaluations are recognized, wide-spread utilization of evaluation systems is not performed. There are several reasons why manufacturability evaluations are not performed more frequently.

The first reason is that the preliminary design phases are characterized by imprecision, but most evaluation systems can only work in a domain of well defined features where the dimensions and tolerances are precisely known. Thus, currently manufacturing evaluation can only be performed as a post-design review. The second reason is that most systems require specialized knowledge, extensive databases, and a significant amount of time and cost. Many small manufacturers, the bulk of the manufacturing industry, can not afford the time and effort required to create and maintain the company specific databases and knowledge-bases required by these systems. Third, these manufacturing evaluation systems only provide estimates of the *most likely cost* [Venkatachalam *et al*., 1993] and convey no information concerning the associated error. Designers also need information on the lowest possible cost and the highest possible cost. Consequently, the current manufacturing evaluation systems are in general not utilized during preliminary design stages and small manufacturers have difficulty utilizing them.

The objective of this paper is to describe a representational scheme being developed for manufacturing process capabilities. The knowledge-base models general relationships for reasoning about the product and provides valuable manufacturability feedback to the designer. The manufacturability evaluation is performed at a qualitative level that is more accessible during the early stages of design and to manufacturers that do not possess the expertise or data required by existing methods.

EVALUATION

Manufacturing evaluation is conducted on the data and knowledge about the manufacturing process capabilities. The evaluation methodology is:

(1) Classification of the part features that affect the process capability evaluation and cost evaluation.

(2) Compatibility evaluation between the part features and the manufacturing process capabilities.

(3) Cost evaluation of the design based on these features using the manufacturing knowledge-base.

Overall, to support manufacturability evaluation the system requires; a part description, manufacturing process capability data, and a knowledge-base to estimate expected cost based on the part features and manufacturing capability information.

CLASSIFICATION

The product profile is the set of part features used for manufacturability evaluation. The overall part has features based on geometry, production, and topology. The classification is performed using rules, that determine to what *degree* a certain feature exists. The general form of the classification rules is shown in Figure 1. The designer is not directly queried to provide the degree of "box-like" shape but to assign values to the measurable quantities of length, height, and projection diameter. This approach is less subjective, since designers cannot be expected to reliably and consistently assign membership values. The features are described by linguistic quantifier terms, so that the shape is "box-like" to a degree of either "high", "medium", or "low". Manufacturing process capability evaluation is less sensitive to errors in degree compared to errors in classification. The example rule shown is used to classify the overall part shape. Shape is used in the manufacturing cost heuristic for injection molding that relates the shape of the part to its cost. The more "box-like" the shape, the higher the tooling cost [Dixon and Poli, 1995].

IF $\frac{Length}{Height} \tilde{\geq} 4$

AND $\frac{Proj\_dia}{Length} \tilde{\geq} 0.33$

THEN (*Box_shape* is *High*)

Figure 1. Example rule to determine the degree the shape is "box-like"

MANUFACTURING PROCESS CAPABILITIES

A *manufacturing process capability* is the physical ability of a manufacturing process to perform one or more feature-generating operations to some level of accuracy and precision [Algeo, 1994]. During the product development process the concern is the ability to realize features on the part by the manufacturing resources. *The manufacturing resources* are the machines, tool holders, and tools used to achieve certain process capabilities. While precise, crisp data is sufficient to represent manufacturing resources [Jurrens *et al.*, 1995], it is inadequate to represent their capabilities.

There are two levels of representing manufacturing process capabilities. The factory level represents the manufacturing capabilities of the entire factory. The machine specific level represents the capabilities of a single machine. Ong and Nee (1995) observe that the process capabilities of many manufacturing processes are not precisely defined. Manufacturing process information is commonly presented as characteristic applications and atypical applications. This is illustrated in Chang and Wysk (1985) for the surface roughness of die casting. Most applications range between 0.8 and 1.6 μm, but some applications are capable of producing between 0.4 and 3.2 μm. Generally, products with features near the boundaries of a process's capability are more difficult to fabricate than features well within the process capabilities.

Data Representation

Fuzzy trapezoidal numbers (TrFN) provide a robust representation scheme for manufacturing process capabilities. A TrFN is a generalization of a crisp interval that has imprecise boundaries. It is represented by a quadruplet as:

$$\tilde{x} \rightarrow \langle a, b, c, d \rangle \quad (1)$$

The interval [*b*, *c*] is a pessimistic range that is a conservative estimate and the interval defined by [*a*, *d*] is an optimistic range which describes possible capabilities but requiring more effort usually at a higher cost [Dubois and Prade, 1988]. This notation can also be used to represent crisp numbers when all the vertices are equal, i.e., $a = b = c = d$. Crisp intervals are represented when $a = b$ and $c = d$.

Figure 2 shows a TrFN, $\langle 70, 100, 2000, 2600 \rangle$ representing the size capabilities of die casting.

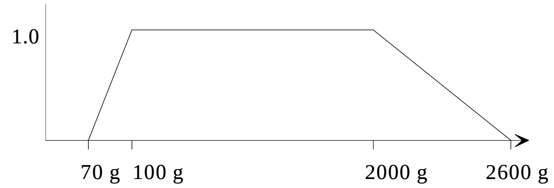

Figure 2. Size capacity for die casting process [Kalpakjian, 1992]

PROCESS CAPABILITY EVALUATION

A compatibility metric between the product profile and the process capabilities is established using possibility theory [Dubois and Prade, 1988]. Possibility and necessity measures assess the ability of a process to form the features defined by the product profile. Both the product profile and the process capabilities are defined using graded sets.

The possibility of a process fabricating the product profile requirements is,

$$Poss\left(R \middle| \tilde{\circ} C\right) = \sup \min\left(\mu_R(x), \mu_{\tilde{\circ} C}(y) \middle| x \in R, y \in C\right) \quad (2)$$

R is the product requirement for a certain feature. The process capability is $\tilde{\circ} C \in \left\{ \tilde{\geq} C, \tilde{\leq} C, \tilde{\cong} C \right\}$, which covers the three possible comparisons. The first represents the preference of being at least equal, preferably greater than. The second represents being at least equal preferably less than. The equality represents the case when there is a single preferred value and values decrease in preference the further from the ideal in either direction.

The necessity metric determines the overlap of the set's core and the requirement. Necessity expresses to what extent the process certainly satisfies the product profile requirements. It performs this by measuring the impossibility of the opposite event. The necessity of the production process x satisfying the condition is defined with the complement of μ_C as,

$$Necc\left(R \middle| \tilde{\circ} C\right) = \inf \max\left(\mu_R(x), 1 - \mu_{\tilde{\circ} C}(y) \middle| x \in R, y \in C\right) \quad (3)$$

There are two types of domains possible. Some of the capability domains are *continuous*, such as size capability. *Discrete domains* are where only a single option of a set of options is possible, such as rotational versus prismatic shape.

The individual compatibility ratings are aggregated to obtain a single measure for the overall part. A compensatory operator, the geometric mean, is used [Klir and Yuan, 1995].

The match between the product profile and the process capabilities determine the feasibility of using the production process to fabricate the artifact. A low compatibility μ_C for a certain process capability indicates that the related features could be changed to improve the design from a manufacturability perspective and thus, possibly avoid production problems.

ECONOMIC EVALUATION

The economic evaluation is manufacturing process dependent. Manufacturing cost is comprised of tooling costs, material costs, processing costs, and labor costs. Tooling and processing costs will be considered here since they are a function of the part features. The objective is to determine a cost range within which the actual cost will occur with a high level of confidence.

Many of the cost models for manufacturing processes are highly detailed and require large amounts of company specific data. It is recognized that a small set of product features have a great effect on the tooling cost and processing cost for many manufacturing processes. For example, undercuts have a significant effect on the tooling cost of injection molding regardless of their shape or size details. Consequently, an evaluation system must only determine their existence, the actual details of shape and size are unnecessary. It is important to make these estimates and feed back the information to the designer. These techniques are also useful to larger manufacturers since they can use them during conceptual design before a complete CAD model is made.

The manufacturing knowledge-base contains the rules that relate the part features to cost. The rules can be used to indicate what changes will most likely improve the design from the perspective of manufacturing. A rule with a low μ value indicates a change to the antecedent can improve the design. Consequently, suggestions for design improvement are made.

The rules are of the general form,

$$\begin{pmatrix} \textit{Feature}_1 \text{ is } \textit{linguistic term} \\ \wedge \ldots \wedge \textit{Feature}_i \text{ is } \textit{linguistic term} \end{pmatrix} \quad (4)$$
$$\rightarrow \textit{Cost} \text{ is } \textit{linguistic term}$$

The operator "is" is a comparator between two linguistic terms [Young, *et al*., 1996].

CONCLUSION

Most existing manufacturing evaluation systems require a CAD model, high levels of detailed data, and specialized knowledge that many manufacturers do not possess. The approach described here is to provide data and knowledge to perform evaluations of designs using a qualitative approach. Fuzzy rules are used to classify the part features. Manufacturing process capabilities are represented as imprecise intervals. Possibility and necessity functions are used to determine compatibility indices between the product features and the manufacturing process capabilities. The multiple ratings are aggregated into a single metric. An economic evaluation is conducted by recognizing that a few features can provide a good estimate of manufacturing costs. The output conveys information on estimated cost and identifies methods to reduce the cost. This method allows designers to evaluate conceptual designs without having a complete CAD model. The linguistic terms used should facilitate manufacturability evaluation performed by designers.

ACKNOWLEDGMENTS

The first author was partially supported as a postdoctoral research associate by the National Research Council at NIST.

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