COST-BASED RANKING FOR MANUFACTURING PROCESS SELECTION

SELECTION DES PROCEDES DE FABRICATION SELON DES CRITERES ECONOMIQUES

A.M.K. Esawi and M.F. ASHBY

*Engineering Design Centre, University of Cambridge, Department of Engineering
Trumpington Street, Cambridge CB2 1PZ, United Kingdom
E-mail: amke@eng.cam.ac.uk*

ABSTRACT

Manufacturing process selection involves two steps. The first involves the *screening* of all available processes to determine whether they are technically capable of making the design; the second involves the *ranking* of those which are successful, using economic criteria. The ranking step requires techniques of cost-estimation. In seeking to achieve this, two problems are encountered. The first: that the design is still in an early stage at which little information is available; the second: that conventional cost-estimation techniques require detailed information and cannot easily be applied to widely diverse processes. A simple approach for this problem is presented. It is based on the idea of a resource-consumption cost model, applicable early in the design process. The system is described and a case study is used to demonstrate how it works.

RESUME

La sélection d'un procédé de fabrication comprend deux étapes. La première consiste à évaluer les différents procédés afin de vérifier qu'ils permettent, d'un point de vue technique, d'obtenir un produit en accord avec les spécifications. La seconde étape consiste à classer les procédés retenus selon des critères économiques. Cette phase fait intervenir des techniques simples d'estimation de coût. Cependant, on rencontre au cours de cette sélection deux types de problèmes. Le premier d'entre eux est lié au fait qu'elle intervient alors que la conception du produit est peu avancée, ce qui limite la quantité d'informations disponibles. D'autre part, les techniques précises d'estimation de coût, qui existent pour certains procédés de fabrication, nécessitent des renseignements détaillés concernant le procédé. L'objet de la présentation est d'aborder ce problème par une approche simple, basée sur l'idée d'un modèle d'évaluation des coûts liés à la consommation des ressources, et applicable au début de la démarche de conception. Le système sera décrit et une étude de cas sera utilisée afin de montrer comment il fonctionne.

I. BACKGROUND

In the early stages of designing a component, the designer is faced with many decisions among which are the selection of the most appropriate *material*, and the most appropriate *manufacturing route* - meaning one that is capable of forming the selected material to the desired shape *economically*. Both have a major impact on performance and manufacturing cost. Computer-aided design tools which help with geometry, manufacture and assembly already exist, and continue to develop. Process selection, however, has received less attention. In this paper, a systematic procedure for process selection is presented. The procedure has been implemented in the *CMS* software [CMS.95], the features of which are illustrated below.

II. THE DESIGN PROCESS

Typically, a product consists of *assemblies* and *components*. For example, the total system of a *car* consists of a set of assemblies, among them the *engine*, incorporating an *ignition system*, of which one unit is the *spark plug*. The spark plug, in turn is made up of individual components such as the *body shell*, the *insulator*, the *electrodes*, etc. Process selection takes place at the component level.

It is conventional (and helpful) to think of the design process as starting with a market need and proceeding through three stages: the conceptual stage, the embodiment stage and the detailed stage. The output of these stages leads to a set of specifications and constraints which dictate how the product should be made. In the conceptual stage of design, little information is available and few constraints have been specified so all possible manufacturing processes should be considered. As the design progresses to the embodiment stage, more information on the product become available and a set of constraints are specified. These are used to determine a subset of processes which are capable of making the product. Finally, as the design reaches its final stages and becomes detailed enough to allow cost evaluation, a single process can be selected. It is helpful at each stage to know the potential processes since this influences the next level of design decisions.

III. COST ESTIMATING METHODS

Cost estimating techniques are of several types, each serving a different stage of the design. In *Function Costing* [WIE.88] [FRE.92] empirical formulae are developed for the cost of a *unit of function* - energy conversion, for example, or pumping, or control. The cost of each sub-system (performing one function) can be estimated from historical data on similar sub-systems or functional groups. These costs are then added together to give the total system costs. *Macro-scaling or "Top-Down"* estimation [WIE.88] [MEI.88] utilises the observation that, for families of related assemblies, the final cost is, very approximately, proportional to the weight, or (better) the cost of the material of which the assembly is made, allowing an approximate scaling for a new product. *The Meso-scaling, or Cost-scaling Method* [ALL.90] adds precision by scaling past costs to new requirements, allowing for change of material, for design features such as size, complexity and precision, and for production information such as batch size; it works well for families of related products. *The Micro-scaling, or "Bottom-Up"* approach starts from a set of engineering drawings for a component of an assembly, and calculates the cost of each operation involved in its manufacture, shaping and finishing. The method requires an intimately detailed description of the manufacturing process and is not a practical approach for the broad, early-stage estimates we seek here, for obvious reasons.

IV. THE CMS SELECTION METHOD

The *CMS* Process Selector makes use of a database which at present contains 125 processes. Each record contains data for the *attributes* of the process: physical attributes such as the materials it can handle, the tolerance, size range, section-thickness and complexity of shape; and economic attributes such as capital cost, tooling cost, and rate of production. The starting point is the idea that all processes are potential candidates until shown otherwise (Figure 1). A short-list of candidates is extracted in two steps. The first, *screening*, eliminates processes which cannot meet the design specification. The second, *ranking*, orders the survivors by economic criteria.

IV.1 Screening

A typical 3-stage screening takes the form of Figure 1. It shows three bar-charts, on each of which a numeric property (for example, tolerance, size) is plotted for a selected class property* (process class, material class, or shape class). The axes are chosen by the user depending on the design constraints. The processes are sorted in order of ascending value of the numeric property, which is plotted as a bar to show its range.

Fig. 1: Stage 1: SCREENING.
1^{ère} Etape: "SCREENING".

The selection is made by placing a selection box onto each chart, identifying the range of tolerance, size, and so forth, specified by the design. The effect is to eliminate the processes which cannot meet the specifications.

IV.2 Ranking

The second step (Figure 2) is that of *ranking*, using an estimate for the cost, *C*, of the product as a ranking-measure. The method uses a resource consumption approach, estimating the consumption of primary resources per unit of output and multiplying these by a cost per resource unit (Table 1). Since all processes consume resources, the method can be applied equally well to very diverse shaping methods.

* The current selector divides materials into 9 classes and shapes into 24 categories. Processes are also divided into classes: *primary*, *secondary*, and *tertiary*; with subclasses under each [ESA.97].

Resource	Symbol	Unit
Materials and consumables	C_m	\$/kg
Capital: cost of equipment cost of tooling	C_c C_T	\$ \$
Energy: power cost of energy	$\dot{P}$ C_E	kW \$/kW.hr
Time: overhead rate	$\dot{C}_L$	\$/hr
Space: area cost of space	A C_S	m ² \$/m ² .yr

Table 1: Primary Resources associated with production.
Les principales ressources associées à la production.

The resulting cost-equation takes the form:

$$C = \left[\frac{mC_m}{1-f} + C_w \right] + \left[\frac{C_T}{\dot{n}} \right] + \left[\frac{\dot{C}_L}{\dot{n}} \right] + \left[\frac{\dot{P}C_E}{\dot{n}} \right] + \left[\frac{AC_S}{\dot{n}} \right] \quad (1)$$

Here C_m is the cost of the material of which it is made, m is the mass/unit of product in kg, f is the fraction of material which appears as scrap, C_w is the cost of the other consumables, C_E that of energy and C_S that of the space associated with manufacture of the product. C_T is the cost of tooling, n the batch size (that is, the production volume), $\dot{C}_L$ the overhead rate, and $\dot{n}$ the rate of production. Tooling has a finite life; it may be necessary to replace it during a production run. We therefore expand the second term (the one describing the tooling costs) as follows

$$\left[\frac{C_T}{n} \right] = \left[\frac{C_{T0}}{n} \left(1 + \frac{n}{n_t} \right) \right] \quad (2)$$

in which C_{T0} is the cost of one set of tooling and n_t is the number of units which can be made before the tooling requires replacement. The tooling cost, C_{T0} , includes the cost of jigs and fixtures which are uniquely associated with the manufacture of the component, but it does not include the capital cost of the equipment or plant itself. That is assigned to the overhead-rate, $\dot{C}_L$, which we write as

$$\left[\frac{\dot{C}_L}{\dot{n}} \right] = \left[\frac{1}{\dot{n}} \left(\dot{C}_{L0} + \frac{C_c}{t_c L} \right) \right] \quad (3)$$

where $\dot{C}_{L0}$ is the basic-overhead rate, C_c is the capital cost of the equipment used to make the component and the interest on that cost, t_c is the capital write-off time, and L is the load factor (the fraction of time over which the equipment is productively used).

Fig. 2: Stage 2: RANKING.
2^{ème} Etape: “RANKING”.

The economic attributes of each process include data for C_c , f , C_{T0} , n_t , $\dot{P}$ and A . These are stored in the database for every process. The remaining parameters – batch size, n , the basic overhead rate, $\dot{C}_{L0}$, the capital write-off time, t_c , load factor, L , cost of energy, C_E and cost of space, C_S – are entered by the user. In the present implementation, a *relative cost* is then calculated by dividing the cost estimate for each process, calculated from equation (1), by that for the cheapest one. With this information a bar-chart is constructed in which processes are plotted in order of increasing relative cost, as suggested in Figure 2. The order depends, of course, on the process attributes, but, importantly, it depends also on the values of the user-selected parameters, most significantly on batch size and capital write-off time. Processes offering the lowest cost are selected by superimposing a selection box onto the bar-chart, as before.

We recognise that accurate cost-estimation requires much more information than this. But accurate costing is not our aim. The software tool described here is designed to help in the early stages of process selection, and to prompt the user not to overlook alternatives. At this stage the aim of an approximate cost-estimation is simply that of ranking. The case study that follows illustrates the method.

V. Case study: Connecting Rod

This component, shown in Figure 3, is made of steel. Its weight is in the range 0.5 - 1 kg, and it has a minimum thickness of 25 mm. The shape can be described as a 3-D solid shape with transverse features. The designer specifies a precision of 0.25 mm. It is desired to make 10 connecting rods. Which process should be used? It is also desirable to investigate if the same process is also competitive if the batch size is increased to 1000.

Connecting rod: design requirements

Material Class: <i>ferrous</i>	Size: <i>0.5 - 1 kg</i>
Process Class: <i>Primary, discrete</i>	Min. Section: <i>25 mm</i>
Shape Class: <i>3-D-solid-transverse features</i>	Precision: <i>0.25 mm</i>
Batch Size: <i>10 or 1,000</i>	

Fig. 3: The connecting rod and its design requirements.
La bielle et ses caractéristiques.

Figure 4 shows a typical selection stage. It is a bar chart of tolerance against shape class selecting “3-D-solid-transverse features” from the shape class menu: it is this which best describes the shape of the connecting rod. The selection box imposes the tolerance requirement of 0.25 mm or better. Two more stages follow* (not shown because of space restrictions); they limit the selection to processes which (a) can shape ferrous metals; (b) can cope with the size of the connecting rod; (c) are discrete (batch-processes); and (d) are able to make the section thickness required here.

Fig. 4: A chart of tolerance against shape class.
Graphe: Tolérance - Forme.

Several processes passed all the previous selection stages. They are listed in Table 2. All of them are technically capable of making the connecting rod. However, it remains to investigate which would be the cheapest process for such a component. This obviously depends on batch size. Two batch sizes were selected and a cost-based ranking step is applied. In Figure 5, a batch size of 10 units was chosen and the cost of making the connecting rod using all discrete processes in the database was calculated. The processes which passed all the previous selection stages are labelled. The same chart is plotted again in Figure 6 - this time for a batch size of 1000.

Manual machining	Investment casting
Automated machining	Replicast
Gravity casting	Closed-die forging

Table 2: Processes for the connecting rod.
Procédés pour la bielle.

* See [ESA.97]

Fig. 5: A chart of relative cost against process class (for 10 connecting rods).
 Graphe: Coût relatif - Procédé (pour 10 bielles).

Fig. 6: A chart of relative cost against process class (for 1000 connecting rods).
 Graphe: Coût relatif - Procédé (pour 1000 bielles).

Six processes emerged as suitable candidates for making the connecting rod. The cheapest process depends on the batch size. According to our cost-based ranking, the most suitable for making a batch size of 10 is *manual machining*. An alternative is *automated machining* - though more expensive for such a small batch size. This is because neither process requires a mould to be made (as for the casting and forging processes). For a batch size of 1000, *automated machining* becomes the most competitive process, followed by *gravity die-casting*.

VI. SUMMARY AND CONCLUSIONS

The designer, in considering alternative choices of manufacturing-process routes for a given component, wishes to rank options by their cost. The cost must be arrived at by a technique which is applicable to all the options - that is, it should be applicable to any shape made of any material, by any process. With this breadth of scope the estimate cannot be accurate - indeed it may be only of the most approximate kind. But the goal here is that of

ranking; and for ranking purposes an approximate estimate is good enough. Realistically, the function of the broad selector described here is to provide guidance in the early stage of design when material and process route are first under consideration; to prompt the user so that potential process routes are not overlooked; and to provide a brief description of the process and its attributes quickly and intelligibly. This, we conclude from our study, is feasible.

Acknowledgements

This work has been supported by the EPSRC under a research grant to the Engineering Design Centre, Engineering Department, Cambridge, UK, and by the generosity of the Körber foundation through the award of the European Prize for Science. It is a pleasure to acknowledge numerous helpful discussions with Ms Elicia Maine and Dr. David Cebon.

References

- [ALL.90] A. J. Allen and K. G. Swift. *"Manufacturing Process Selection and Costing"*, Proceedings of the IMechE Part B - Journal of Engineering Manufacture, Vol. 204, 1990, pp. 143-148.
- [ASH.92] M. F. Ashby. *"Materials Selection in Mechanical Design"*, Butterworth Heinemann, London, UK, 1992.
- [CMS.95] CMS Software, Granta Design Limited, Trumpington Mews, 40B High Street, Trumpington, Cambridge CB2 2LS, UK, 1995.
- [ESA.94] A. M. K. Esawi. *"Systematic Process Selection in Mechanical Design"*, Ph.D. thesis, Cambridge University Engineering Department, UK, 1994.
- [ESA.97] A. M. K. Esawi and M. F. Ashby. *"Computer-Based Selection of Manufacturing Processes"*, Cambridge University Engineering Department, Report No. TR50, May 1997.
- [FRE.92] M. J. French. Private communication, 1992.
- [MEI.88] C. J. Meisl. *"Techniques for Cost-estimation in Early Program Phases"*, Engineering Costs and Production Economics, Vol. 14, 1988, pp. 95-106.
- [WIE.88] L. S. Wierda. *"Production Cost-estimation by the Designer"*, Engineering Costs and Production Economics, Vol. 13, 1988, pp. 189-198.