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Process selection for the design of Aluminum components

Jyh-Cheng Yu*, Sherveen Lotfi, and Kos Ishii

Department of Mechanical Engineering, The Ohio State University, 206 W 18th Ave., Columbus, OH 43210-1107, USA

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Andrew Trageser

Product Design and Mechanics, ALCOA Technical Center, ALCOA Center, PA 15069, USA

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This paper describes a method for the process selection of aluminum components in the early stages of design. Aluminum has many advantages in a variety of applications in its manufacturability and recyclability. Yet, engineers who are trained to design steel components do not take full advantage of this material. The main reason is that engineers tend to be unaware of the many economical processing methods for aluminum. We have developed a program that combines the preliminary screening of processes with normalized cost analysis. Design compatibility analysis (DCA) ranks each process based on its feasibility with the basic geometry, material, and production requirements. For top candidates, the program employs external cost routines for detailed comparisons. The primary processes considered are extrusion, sheet forming, forging, die casting, and sand casting. The program extends its compatibility and cost analysis to secondary operations such as bending and machining. The program should be helpful to engineer training and as a preliminary design tool. The program uses HyperCard as a front-end, Prolog for logic-based analysis, and Excel for cost calculations.

Keywords: aluminum part design, aluminum manufacturing processes, process selection, design for manufacture, design compatibility analysis, expert system.

1. INTRODUCTION

1.1 Motivation

The desire to increase the efficiency and performance of vehicles, such as automobiles, railcars, and trucks, has sparked interest in using lightweight materials for the design of these products. Aluminum is one material that is often thought of as a light alternative to steel. The selection of any material has far-reaching effects on the manufacture, assembly, and performance of the final product, making material selection an essential part of concurrent engineering.

With the selection of aluminum, many processing options are available to the designer, who may only be versed in sheet formed and machined steel process paths. Aluminum processing includes the ability to extrude complex cross-sections and cast thin-walled, complicated geometries with local reinforcement and stiffening. Proper selection of an aluminum process path (e.g., extrusion, casting, forging, or stamping) can allow the flexibility to design the product with a reduced number of discrete parts and lower tooling costs.

In the preliminary stages of design, engineers usually check a number of process options for feasibility against geometric, structural, and production requirements for the part. At this time, they may combine processing steps with improving the feasibility of a primary process. For example, the bending or machining of an extrusion makes a non-prismatic yet, extruded geometry. In this example, an extrusion process may be more economical than casting because of the lower tooling cost or more expensive than casting because of the complexity and number of secondary operations.

*Corresponding Author: jcyu@nkust.edu.tw

A screening tool to check the feasibility of various processes would be useful to flesh out concepts before proceeding with a detailed design. Moreover, a process selection tool such as this would educate design engineers about the various aluminum processes available and the factors that govern their applicability.

1.2 Related Work

The past ten years have seen a surge of research and development work involving design for manufacturing (DFM). Perhaps the most notable work was in design for assembly (DFA) pioneered by Boothroyd and Dewhurst (1983). DFA recommends separate parts to be integrated into one unless there is a compelling reason not to. Integration of parts usually leads to a different process, typically a near-net-shape process like die casting or injection molding. Yet, DFA only focuses on assembly cost and does not take into account possible increase in part cost. Cutkosky et al. (1989), Shah et al. (1990), and many others address the machining process. Our work focuses on design for net-shape manufacturing. Ishii et al. (1989) looked at the design for injection molding, while Liou and Miller (1991) focused on design for die casting. In Maloney et al. (1989), we focused on the compatibility between forging designs and the proposed process and equipment. Each work cited above concentrates on a single process and deals more or less with a detailed design suitable for the process in question. Work that addresses the comparison between more than two processes is not generally available.

Many textbooks and handbooks describe the pros and cons of different manufacturing processes. Some handbooks even identify major factors that influence process selection and provide qualitative guidance. Of the many sources available in print, perhaps the most comprehensive is by Bralla (1986). He provides excellent coverage of primary manufacturing processes and comments on their suitability regarding materials, mechanical properties, general shape and size, and production volume. However, he does not deal with the iterative nature of some decision factors such as production volume and cost, e.g., the more you make, the lower the price, thus more sales. Also, the book documents the decision variables and the influencing factors in a "Tree format." They are not completely uniform across different processes. This format sometimes makes it difficult to compare the suitability of one process to another. Many other books provide similar information with a focus on different processes. Ludema et al. (1987) look at the economic aspect of process selection, while Bolz (1974) combines mechanical requirements with cost issues. Eary and Johnson (1962) provide comprehensive coverage of various manufacturing processes, but this information is now slightly dated.

Despite the abundance of literature on manufacturing processes and DFM methodologies for individual processes, very little work has been done in developing a computer-aid that accommodates information about different (old and new) processes, evaluates the suitability of each process with designers' needs, and assists in selecting the most appropriate process.

Process-based group technology represents the most notable attempt at guiding designers in process selection. Niebel (1966) devised a group technology system for a wide range of manufacturing processes and proposed a decision equation that approximates the cost per part of the primary operation. While his method provides a good "First cut" comparison of different processes, the system only addresses a relatively rough geometry classification (9 classes), materials, and lot size. Group technology normally addresses one classification factor, e.g., shape. Extending beyond one classification factor is not trivial. Therefore, group technology works well when it addresses either a single process or processes that lead to similar geometry classifications.

1.3 Our Approach

Our previous work on process selection focused on general net shape manufacturing (Ishii et al. 1991; Yu et al. 1992). Design compatibility analysis (DCA) (Ishii et al. 1988; Ishii et al. 1991) formed the basis of our proposed method for the preliminary screening of manufacturing processes. DCA compiles the compatibility information in an object-oriented representation called C-data. The computer program for process selection used the c-data to assess the suitability of candidate processes to a given set of inputs: geometry classification, materials, and production specifications.

This paper extends our previous method to aluminum processes. The main features of the extensions are 1) a more detailed geometry classification for aluminum processes, 2) a combination of the heuristic guidelines with available cost information, and 3) consideration of commonly used secondary processes. Most of our efforts address the representation of compatibility data. In particular, the secondary process capability requires some of the compatibility rating to adapt dynamically to different specifications of secondary processes.

Section 2 of this paper examines the challenges in aluminum process selection and describes our methodology using DCA. Section 3 illustrates the structure of the program. Section 4 provides an illustrative example, and Section 5 presents conclusions and future directions of research.

2. PROCESS SELECTION METHODOLOGY

2.1 Processes under Consideration

This paper covers the following net-shape processes:

(1) **Forging** applies to parts such as connecting rods, hand tools, bolt heads, and wheels. Forged parts retain good mechanical strength and a high strength-to-weight ratio. They also minimize scrap losses and contain very few internal flaws. However, forging is costly and often requires expensive secondary machining to impart good dimensional accuracy.

(2) **Sheet forming** involves reshaping flat sheets into parts with complex surfaces, such as appliance bodies, beverage cans, car bodies, and aircraft panels. The complexity of forming operations ranges from simple bending to a sequence of multiple action press operations. Tooling cost increases with part complexity, but labor requirements are low, making sheet forming ideal for making large numbers of parts.

(3) **Extrusion** is the process of pushing a high-temperature billet through a die to form a length of a constant cross-section. Factors that influence extrudability are alloy type, part shape configuration, dimensional tolerances, and surface finish requirements. Extrusion allows for complex cross-sectional shapes and keeps tooling costs at a minimum. The size of the extrusion press limits the size of the cross-sectional area.

(4) **Sand casting** is the process of pouring molten metal through a set of runners into a disposable sand mold. Intricate shapes can be attained with low tooling costs, making sand casting attractive for low production volumes.

(5) **Permanent mold casting** consists of repeatedly using a metal mold to produce castings of the same shape. It is suitable for high production volumes and will produce parts that possess good dimensional accuracy and a smooth surface finish. However, there are limitations on the size and the complexity of the part and on the alloys which can be used.

(6) **Die casting** consists of forcing molten metal under pressure into metal molds called dies. Metal flows at high velocities induced by the application of pressure. High pressure die casting has emerged as the preferred method over other casting methods in response to product design requirements for thin walls, complicated shapes, and the demand for closer tolerances.

2.2 Criteria Influencing Process Selection

The major factors that influence process selection are classified into three categories:

(1) Material Factors:
  a) Mechanical Properties
  b) Physical Properties
  c) Alloy Specification

(2) Geometry Factors:
  a) Part Shape
  b) Part Envelope Size
  c) Part Weight
  d) Dimensional Tolerance
  e) Surface Finish
  f) Secondary Operations

(3) Production Factors:
  a) Lead Time
  b) Production Volume
  c) Production Rate

The dependency between factors differs from product to product. The sequence in which designers make choices about each variable depends on the relative importance of the functional requirements of a product. In some cases, such as electronics housing, the mechanical and environmental requirements give the designers a wide range of materials. Hence, designers are likely to determine the process (die casting or sheet metal forming) before choosing the material. Naturally, the detailed design of the part and the determination of process parameters such as machine size and process conditions come after both material and process selection. In essence, designers must resolve the major factors *simultaneously* to select the appropriate process.

2.3 Compatibility Data

Traditional process selection procedures require the design engineer to go through volumes of handbooks and checklists. Engineers need to compare the possible manufacturing processes in light of multiple factors simultaneously. In comparing several feasible candidate processes, engineers often rely on cost estimation procedures to determine the most appropriate process, requiring detailed part geometry and production specifications. The task requires the engineer to retain design, manufacturing, and management expertise, which is a challenging task, particularly if one wants to include novel processes.

The main objectives of our research are as follows:

(1) Develop a representation scheme for the compatibility measure of a candidate process.
(2) Construct a methodology to evaluate compatibility early in the design stage.
(3) Estimate relative part cost for comparable processes based on the given design.

Some of the decision factors tend to be rather uncertain in the early stages of design. Thus, our program first utilizes case-based knowledge that addresses the compatibility of each process with the product specifications. If more than one process is applicable, the relative part cost of each process is used as the deciding factor.

The hypothetical cost vs. volume curve shown in figure 1 illustrates the points at which the best processing choice will change. The issue is to identify the basic factors that control the location of such breakpoints and establish methods to estimate the incremental tooling costs that determine them. Naturally, we must also incorporate into our compatibility consideration other factors such as the tolerance requirement and the time to market.

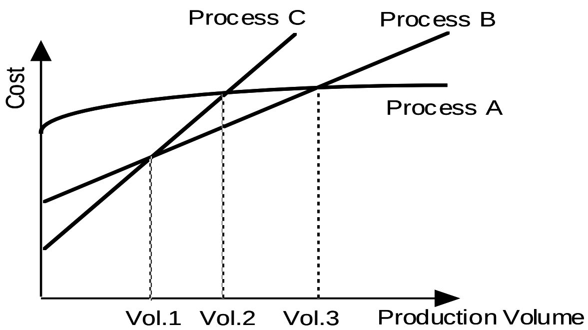

Figure 1. Incremental Tooling Cost Breakpoints.

Our prototype program, ALPRO, adopts a case-based compatibility representation, i.e., excellent, poor, and incompatible examples of preliminary geometry as a function of the selected process. Our original work on design compatibility analysis (Ishii et al. 1988) focused mainly on the qualitative design rules compiled as good and bad templates of design. Each template, called a C-data, has a qualitative rating, justification for the rating, and suggestions for improvement. The qualitative rating is later mapped to a number between [0,1]. This application uses the adjectives [excellent, good, fair, poor, bad, incompatible] to represent the ratings [1.0, 0.8, 0.6, 0.4, 0.2, 0.0]. We group the template by the factor it addresses.

$$\text{Decision Factor Space } XF = X_1 \times X_2 \times \ldots \times X_n \quad (1)$$

where X_i = Universe of discourse of the decision factor i

The C-data comprise a set of data called the Compatibility Knowledge-Base (*CKB*).

$$CKB = \{C\text{-}data \mid C\text{-}data \subset X \times P \times SP \times [0,1]\} \quad (2)$$

where $X \subset XF$

P = Universe of discourse of the process

SP = Universe of discourse of the secondary process

2.4 Secondary Operations: Dynamic Compatibility

There is generally more than one feasible net-shape process to produce complex parts. Variations arise from the number and type of secondary operations applied in the process plan. For instance, in the case of close tolerances or additional geometric features, it is sometimes possible to bring the part closer to a final shape with more complex and elaborate tooling or tighter process control. The use of more sophisticated tooling reduces or eliminates secondary operations but causes higher tooling costs and may involve higher operating and maintenance costs. An alternative method is to choose a less sophisticated process and apply some simple additional operations to add features that are difficult to form, to bring dimensional tolerances within limits, and/or to improve the microstructural properties of the part. Thus, the decision factor becomes the overall manufacturing cost of the part.

Let us give an example C-data related to surface finish. Figure 2 shows the surface finish capability of various manufacturing processes (Bralla, 1986). If the user-specified surface finish falls in the "Average Application" capability range of a certain process, the compatibility is "Excellent." If the user specification corresponds to the less frequent application" part of the band or if the requirement is less constrained, i.e., falls to the right of the range, then the compatibility is "Fair". Obviously, if the specified surface finish is finer than the capability band, i.e., falls to the left of the band, the rating will be "Incompatible."

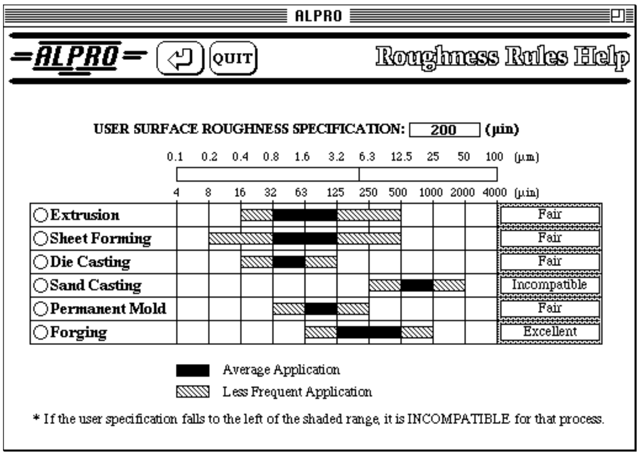

Figure 2. Surface finish capability of manufacturing processes

However, if the designer would like to apply secondary operation, such as surface finishing, the incompatible primary process becomes feasible. In this case, we change the rating to "Poor", below neutral rating 0.5, since the process becomes compatible but should be penalized in the DCA rating for its additional cost.

For those factors incompatible with the primary processes, the compatibility will be "Dynamic" since it depends upon whether we could correct them using secondary operations. If the incompatible factor is correctable and the designer would like to choose this option, the final compatibility rating of this factor is "Poor"; otherwise, the process will be "Incompatible." The designer, however, needs to tradeoff between the more sophisticated net-shape process and the combination of the rougher but cheaper process and some secondary operations.

This qualitative information yields a set of C-data. Equation (3) logically represents an example of C-data.

C-Data (ID_number : geo_ROFd4
Factor : Geometry
Descriptor : incompatible
Reasons : DCA of Process/Roughness is incompatible if the user's roughness specification is finer than the normal surface finish application of the process.
Conditions : Selected_process = Die_casting
Roughness_spec < 16
No secondary operation of surface roughness) (3)

3. EVALUATION METHODOLOGY

3.1 Design Compatibility Analysis

Design compatibility analysis (DCA) measures the compatibility between the decision factors and the candidate process (Ishii et al. 1988). For each of three categories (i.e., material, geometry, and production), DCA compiles the compatibility object that "Matches" a particular situation then takes the most extreme rating (i.e., if there is more than one "Negative" comment, DCA takes the worst comment; otherwise, it will adopt the best comment). If no compatibility data matches, DCA gives a neutral value of 0.5. Hence,

$$DCA: X \times P \times SP \times CKB \rightarrow [0,1] \quad (4)$$

Namely, DCA is a mapping from the decision factors, the candidate process, and the compatibility templates to a normalized evaluation. Therefore, we obtain three sub-ratings from the material, geometry, and production factors. The overall match index is defined (Yu et al. 1992) as

$$MI_{overall} = \sqrt[3]{\prod_{i=1}^{3} M_i} \quad (5)$$

Based on this scheme, DCA gives a zero overall match index whenever there exists any totally incompatible factor with the process in the user's specification.

Figure 3 shows the schematic of DCA using case-based compatibility rules. The figure illustrates the "Simultaneous" nature of the evaluation process. Once the user specifies the values of various decision factors such as production volume and surface roughness, DCA scans through the compatibility knowledge-base for each candidate process and determines which C-data matches. Based on the number and the nature of applicable C-data, DCA determines a sub-rating for each category and evaluates the geometric average of the three sub-ratings for the overall matching index. In short, the rating scheme is:

(1) Sub-rating M_i for each factor category
  a) 0.5 if no C-data matches
  b) The sub-rating that corresponds to the worst adjective, if there is at least one negative comment in this category
  c) The sub-rating that corresponds to the best adjective, if there are no negative comments in this category
(2) Overall matching index $MI_{overall}$ = the geometric average of the three sub-ratings M_i.

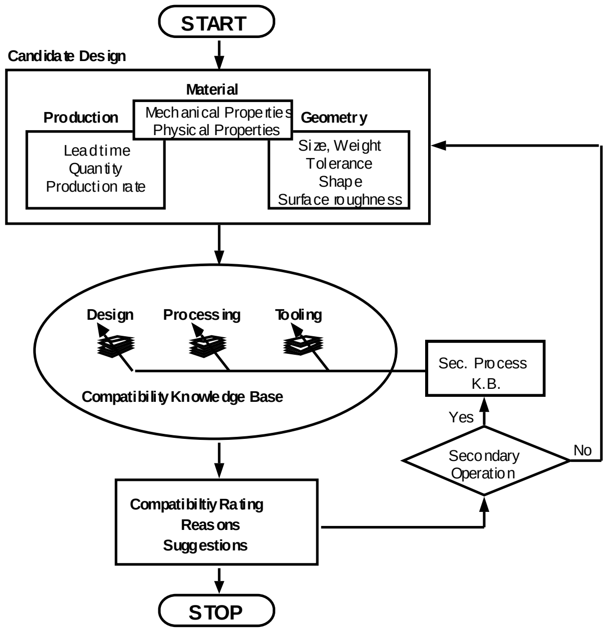

Figure 3. Schematics of Case-based DCA

This method has proven effective in the very early stages of design when there is little quantitative cost data available. We view this overall matching index to be a normalized estimate of production cost per part.

The idea behind our expert system for screening potential manufacturing processes is to use DCA to rate each candidate. For those compatible processes, designers may want to focus on the top two or three candidates and proceed with a detailed analysis based on these candidates. Therefore, from the appropriate C-data, they can identify key factors influencing a poor rating. Designers have the option to either relax unnecessary specifications or look for an alternative process to improve the design's manufacturability. As more detailed information becomes available, designers may wish to employ a more quantitative measure of process compatibility, such as cost estimate intervals (Ishii, Lee, and Miller, 1990).

Nevertheless, the screening procedure based on case-based knowledge will provide the designer with a focused view of possible manufacturing processes and encourage him to consider tailoring part designs for the candidate processes. Such consideration can greatly enhance design for manufacturability and reduce the life-cycle cost of products under development.

3.2 Cost Considerations

Ultimately, the selection of a specific process reduces to the calculation of the part's cost relative to other candidate processes. Assuming that the design criteria are compatible with a process, we can calculate a part's cost using a formulation that includes such things as tooling, material, and labor cost. The basic equation that we will use for estimating part cost is:

$$C_p = \frac{C_T + C_L + C_M + C_S}{V} \qquad (6)$$

where C_p = Part Cost
C_T = Tooling Cost
C_L = Labor Cost
C_M = Material Cost
C_S = Secondary Machining Cost
V = Production Volume

Although much more elaborate and proprietary models for cost calculation exist, this equation will serve well as an engineering estimate of the relative costs involved in each process. The only conspicuous component of the above formulation is the portion involving secondary costs. In general, this factor includes parameters that an engineering economist might take into account, such as the cost associated with producing the part at a specific plant or the costs that may be associated with a particular design's testing and development. In our case, we will use the secondary cost component to reflect the additional costs due to any secondary operations that may be required.

In some cases, the cost increase due to secondary operations is simple to calculate. For example, we can calculate how much it will cost to bring the surface roughness of a sand cast part into a feasible range by subtracting the user's specified roughness from the best roughness that sand casting is capable of. There are specific cost increases associated with changing a dimension's tolerance specification outlined by Bralla (1986).

In situations where secondary operations are performed to change to the general shape of the part, cost increases are much more difficult to estimate. If the part's geometry is defined rigorously, as would be the case with a complex CAD solid model, we could associate a specific cost with any possible change in geometry that could take place. For example, if the designer wanted to drill some extra holes into a part after it has been extruded, we could simply add an amplification factor for each different hole that the designer would like to drill.

4. IMPLEMENTATION AND SAMPLE RUN

We have implemented our proposed procedure using HyperCard and Logic Manager, an implementation of Prolog developed by Apple Computer. The prototype program, called ALPRO, is structured as illustrated in figure 4.

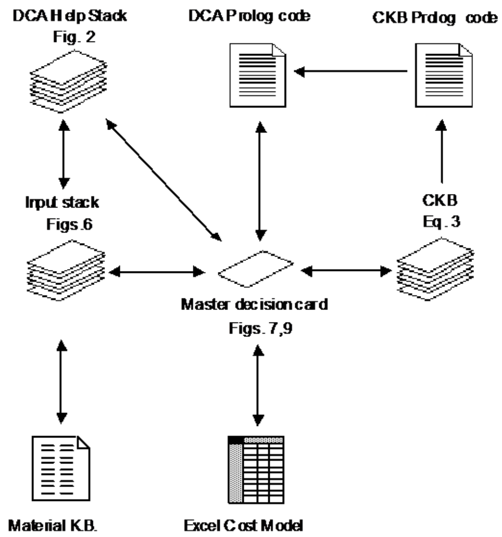

Figure 4. Program Structure of ALPRO

The ALPRO rule base consists of over 250 C-data along with over 30 inference rules related to characteristics of each manufacturing process. To perform the cost calculation, the program uses a Microsoft Excel spreadsheet macro that reads data from ALPRO, calculates the part cost for each compatible process, and creates an output file. The output file is then read into ALPRO, and the data is displayed.

This section gives an example case of how ALPRO can be used to find an appropriate process for a given part design. Figure 5 shows a proposed part design. The tightest dimensional tolerance is ± 0.05 inch (± 1.27 mm). The estimated production volume is 3000 pieces, and the surface finish requirement is 50 micro-inch (1.27 micro-meter). We will also constrain the design to 5.8 lb (2.63 kg) maximum part weight and a lead time of 20 weeks.

ALPRO accepts the user inputs through interaction cards in three modules: 1) material factors, 2) geometry factors, and 3) production factors. Figure 6 shows an example of these input cards with the navigation pallet. The user interface is designed to provide user-friendly data entry and online help.

After the user specifies the required input variables, ALPRO uses case-based knowledge and DCA to rate the compatibility of each process. In our example, DCA indicates that only two out of the six possible processes are compatible with the given design constraints. The cumulative results for each of the six processes are displayed, as illustrated in Figure 7.

Designers can also get details about why each process received its rating. Figure 8 shows the rating breakdown for extrusion relative to each of the three major categories. This card gives a breakdown of how each process fared in each category and shows exactly which rules fired for each of our specifications. We can see under the geometry criteria that while all other specifications were at least “Good,” the part shape we chose is incompatible with the process. Similarly, we can see that the production criteria were excellent, i.e., both the production volume and the lead time specifications were very well suited for extrusion. The materials field indicates that no rules matched our specification (we did not choose an alloy for our design), so the program can make no judgment.

We can take the breakdown into an even finer level of granularity by showing why a specific rule was fired. For example, you may want to know why forging received a poor rating for production volume. You can get help information about production volume by clicking on the “Production Volume” rule that will have fired. This help card displays the minimum economic production quantity associated with each process. It would show that the break-even point for forging generally falls at 5000 pieces that is the minimum number of parts that must be forged for the process to be economically feasible. Since this specification is higher than the 3000 pieces that we specified, forging would receive a poor rating. Online help cards such as this are available for each criterion to help users see how their design decisions influence the compatibility rating.

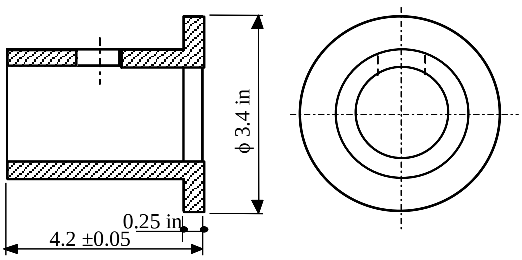

Figure 5. Example Part

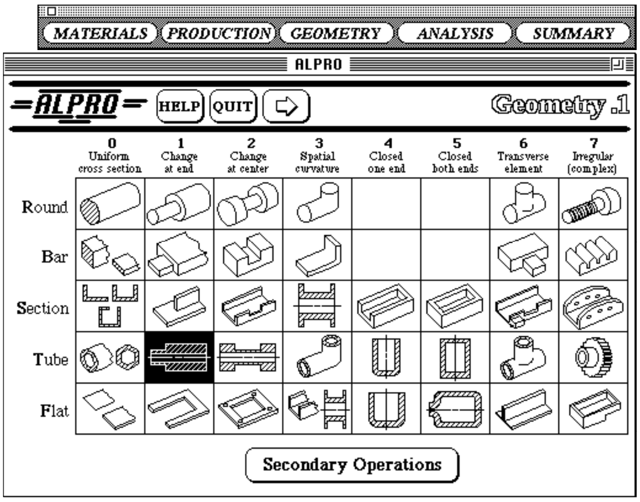

Figure 6. Classification of part shape

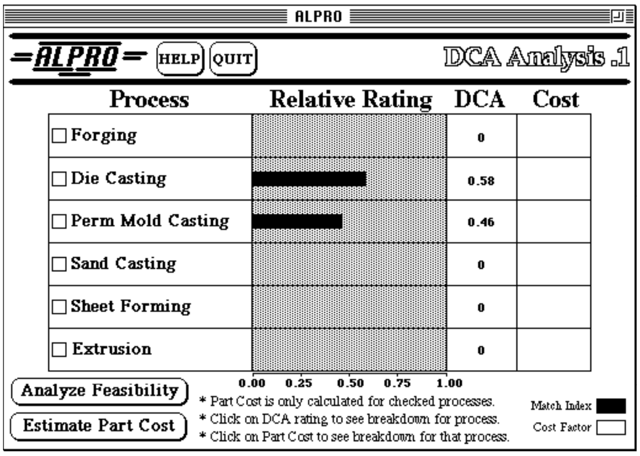

Figure 7. Process Ranking Card

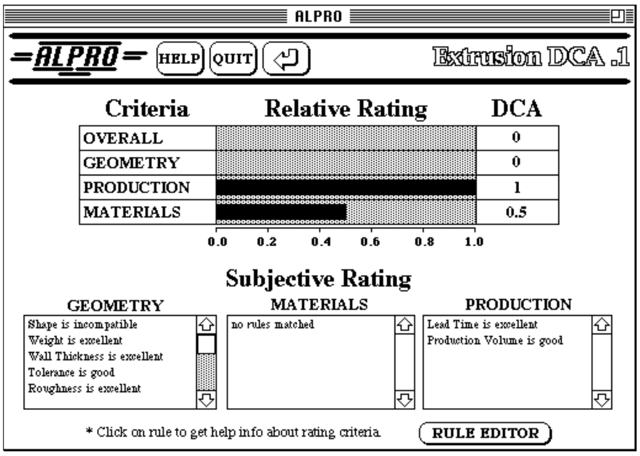

Figure 8. Detailed DCA for Extrusion

This kind of case-based knowledge allows the designer to carefully look back at the design specifications and reconsider whether some of the design factors can be changed without sacrificing any of the part’s functionality.

For example, if the dimensional tolerance and the surface roughness values can be relaxed, then sand casting will be added to the list of candidate processes. On the other hand, if we tighten the dimensional tolerance to ± 0.001 inch, none of the processes would be compatible. In this scenario, a two-step process plan with sand casting followed by machining may be cost-effective. The use of sand casting as the primary process would minimize the amount of material to be removed, resulting in lower total cost than machining from raw stock or using a process with high dimensional accuracy such as precision forging. This part cost is a primary consideration in process selection methodology.

We can calculate a primary cost for the processes that are initially compatible. In our example, we can make an estimation of the part cost for die casting and permanent mold casting. However, as we mentioned before, we may be able to perform secondary operations on sand cast parts to increase dimensional accuracy and satisfy surface roughness requirements. We call this the *secondary compatibility* of a process. Originally sand casting was not feasible, but with the inclusion of secondary operations such as sanding, finishing, etc., it can be made compatible.

In ALPRO, we can indicate that we would like to perform secondary operations by checking off what we think we may be able to do to make a process compatible, i.e., surface finishing and machining for castings, flanging or bending for extrusions and sheet formed parts. If we specify secondary operations to correct the tolerances and finish the surface of the part, the compatibility ratings of the six processes will change. In our example, we would notice that given these secondary operations, forging and sand casting now become feasible. Assuming we have provided ALPRO with all the necessary information, we can calculate the part cost for each feasible process. In this case, the program will ask us to declare a material specification since this missing factor was not necessary for the original compatibility analysis.

It may be the case that the incompatibilities of sheet forming and extrusion are due only to our choice of geometric shape. The part we selected does not have thin walls, nor does it have a constant cross-section area. In such cases, we ask the user if he/she thinks that secondary operations may correct the initially incorrect shape by extra machining, etc. The user may indicate a percentage increase in cost that secondary machining will levy on the original part cost and can subsequently make each process compatible. Since we lack a rigorous CAD model of the part that would allow us to gauge shape deviations between the designer's intended design and a generally compatible shape classification, we are forced to ask the user to make this distinction. For example, our shape can be made extrudable by flanging one of its edges and drilling a hole through its main hub.

Once we perform the cost analysis using an external Excel Macro, the results look like those displayed in Figure 9. Each of the costs increases due to secondary operations (surface finishing, tolerance correction, and any shape modification) is added to the original part cost to come up with the final figure. ALPRO can also give us a breakdown of the cost- i.e., what would the original cost have been without secondary operations, and what percentage of the final cost can be attributed to each secondary operation.

The selection of a specific alloy has influenced the compatibility of the originally feasible processes. Die casting and permanent mold casting are no longer feasible. The figures in the Cost column are relative comparisons of the part cost for each process. The white bars graphically show how the costs compare. As the cost model becomes increasingly accurate, the figures will approach the actual cost of the part.

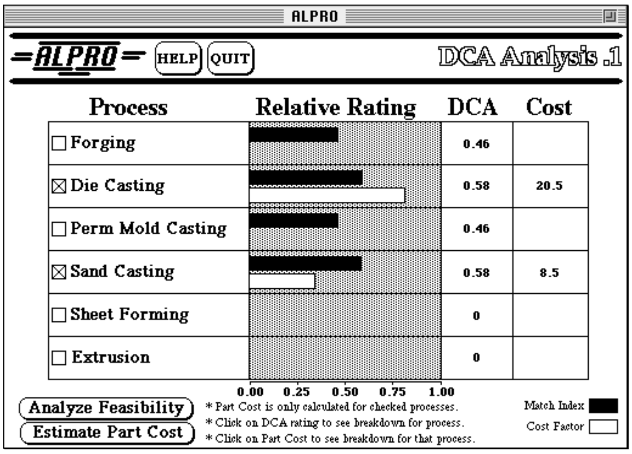

Figure 9. Cost Analysis Results

5. Conclusions and Future Directions

This paper described the development of a design for process selection that focuses on aluminum and other competing materials and for 6 representative processes: 1) forging, 2) permanent mold casting, 3) sand casting, 4) die casting, 5) sheet forming, and 6) extrusion. The program asks the users to specify the material used, geometry types and other specifications (wall thickness, surface quality, tolerances, etc.), and production volume. Compatibility guidelines perform a feasibility check and rank the candidate processes using a normalized measure (preliminary screening). The program also includes interfaces to ALCOA's proprietary cost equations which allow the users to perform detailed comparisons of the top candidates. The most significant development is the concept of dynamically adapting compatibility data to accommodate secondary processes.

Our future tasks include the following fundamental challenges and program extensions:

(1) Identify important inputs that characterize the functional specifications (e.g. strength, weldability, surface finish, corrosion, etc.)

(2) Incorporate a method for material selection
(3) Develop normalized cost measures based on functional features
(4) Expand the analysis to compatibility among functions, material, process, and geometry
(5) Develop a more detailed identification of cost-driving part attributes

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