A System for Generating Process and Material Selection Advice During Embodiment Design of Mechanical Components

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ABSTRACT

This paper describes (1) a systematic approach to material and process selection during embodiment design of mechanical components, (2) algorithms for supporting various steps in our approach, and (3) a system for generating process and material selection advice. Quite often during embodiment design stage, design requirements are not precisely defined. Therefore, our system accounts for imprecision in design requirements during generation and evaluation of alternative process sequences and material options. To reduce the computational effort, our system uses a depth first branch and bound search algorithm. This aids in exploring promising process sequences and material options that can be used to meet the given set of design requirements. Various process sequences and material options are evaluated by using a commercial cost estimation tool. Using our system, designers can consider a wide variety of processes and materials during the embodiment design stage. Therefore our system helps them in finding the most cost-effective combination. Moreover, by selecting processes and materials during the design embodiment stage, designers can ensure that the detailed design is compatible with all of the constraints for the selected material and processes.

1. INTRODUCTION

Design of a product requires the satisfaction of a set of functional requirements. In addition, there are sets of manufacturing process-dependent constraints that must also be satisfied in order to produce the individual components comprising the product. Designers, therefore, must satisfy both types of constraints. In most designs, process constraints play a significant role in determining the detailed features of the final form of the components. Moreover, there is usually more than one manufacturing process that can be used to manufacture these components. Therefore, the satisfaction of a given set of functional constraints can be realized by components that can appear in many different forms, depending on the process constraints. For example, consider the case of a support base that is to provide a mounting face, a support face, and a certain load-carrying capacity. As shown in Figure 1, this base can take many embodiments. For example, Figure 1(a) shows the desired process independent functional design. Figures 1 (b), (c), (d), (e), (f), and (g) show designs for sand casting, powder metallurgy, forging, welding, milling, and bending respectively. This example illustrates that the final form of a component can be specified only after selecting the most appropriate process and material combination. Usually cost considerations play a major role in the final selection of the process and material combination.

Traditionally, designers select process and materials using either their own previous experience, or the experience of the manufacturing engineer. Boothrooyd et al. [Boothroyd et al 1994] point out that most designers are familiar with very limited number of manufacturing processes. Therefore, if designers rely on their own knowledge, they might not consider unfamiliar manufacturing processes that may turn out to be an attractive alternative to the processes known to designers. This is increasingly becoming a problem in today's era of rapid changes in manufacturing technologies. This makes it difficult for a designer to be familiar with all the manufacturing processes. Many designers approach manufacturing process providers and ask them for advice on the process and material combination. If the design task is not very complex, manufacturing engineers can use their knowledge of the manufacturing processes and materials to suggest a possible combination that would produce the design. As this step is done manually, it is very likely that manufacturing engineers may not be considering all the available processes and materials. Moreover, they may not even be aware of the existence of certain processes and materials. Hence, even if their suggestions help the designer realize his or her design, it may not be the optimal choice.

There exist a large number of manufacturing processes and materials that are known and are being used widely all over the world. Each of these processes and materials has its own capabilities and characteristics. It may not be possible to produce a given design by some of the process and material combinations. As these combinations are numerous, the designer may have to spend enormous amount of time trying to find out the right process and material combination. Hence, in a realistic scenario, it is not possible for the designer to be able to get an optimal process and material combination by evaluating all possible combinations himself or herself. It would be helpful to have a process and material selection service where all the available processes are registered. The designer would only have to submit his or her design to this service to get the advice on the possible processes and the materials. This kind of technology will help in reducing the time taken from the conceptualization of the design to its physical realization.

According to one popular school of thought, design activity can be divided into three main stages: conceptual design, embodiment design, and detailed deign [Pahl and Beitz 1996]. The SIMA reference model decomposes these stages further [Barkmeyer, et al l997]. The purpose of conceptual design is to identify essential problems and provide working concepts. At this stage generally there is only information on functions and principles. For example, a functional requirement of the product might be to change hydraulic energy to mechanical energy, and the corresponding principle chosen could be screw motor. At the conceptual design stage, there is only abstract information about the design. Therefore, it is difficult to start process material selection. The purpose of embodiment design is to determine the overall layout design and the preliminary form designs. According to Pahl and Beitz [Pahl and Beitz 1996] --- "During the embodiment phase, at the latest, the designer must determine the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and material) and the production procedure, and provide solutions for any auxiliary functions." The steps described above change the abstract design information into quantitative information. Therefore at this level there is sufficient information for starting process and material selection. Furthermore as illustrated in Figure 1, before proceeding with the detailed design, material and processes should be known in order to ensure that the final form incorporates the process constraints.

To finalize the detailed design of the part, we need to find a material that can meet the material requirements and a process sequence that is compatible with the material and can meet the form requirements of the function. Furthermore, the material and process sequence should meet business requirements such as quantity, production rate, and tooling lead-time. Many different types of materials and processes may be available to the designer. The set of available materials needs to be defined based on the company's policy. If the component needs to be produced using the existing resources, then this set will consist of the materials in which the company has prior experience. If outsourcing is being considered, then all possible choices available from the company's supplier-base should be considered. If procuring new equipment is also a possibility then all possible known materials should be considered. To consider all available materials and processes systematically, the following three steps need to be followed:

1. *Option Filtering:* The purpose of this step is to prune all those combinations of materials and processes that cannot meet the design requirements. First, all available materials should be considered and materials that do not meet material requirements should be pruned. For each material that has not been pruned, all compatible processes should be considered, pruning those that cannot meet design requirements.

2. *Option Evaluation:* All material and process sequences generated from the previous step will be considered during the evaluation step. There can be many evaluation criteria, such as manufacturing cost, tooling lead-time, etc. Due to imprecision in design parameter values, cost estimates will also involve uncertainty. Such uncertainty needs to be considered as a part of the evaluation step.

3. *Selection*: Based on the cost evaluation results and other important criteria, the final decision needs to be made regarding the combination of materials and processes that best suit the design requirements and objectives.

The above three steps need to be performed during the embodiment deign stage. It is not necessary to complete Step 1, before commencing with Step 2. Sometimes after doing preliminary filtering, the second step can be started and additional filtering can be done as a part of the second step. After these steps, based on the selected processes, the final form should be designed (during the detailed design) such that it incorporates process constraints associated with the selected processes. An example of such constraints is incorporating required draft angles into the final form if the selected process is sand casting.

The following aspects need to be addressed during material and process selection.

- *Coupling between material, size, and processes*: Whether or not a process can be selected depends on both the material type and the component size. In many cases, component size cannot be defined without knowing the material type and the process cannot be selected without knowing the size. Therefore, it is difficult to treat this problem as a single database look-up problem.

- *Cost Interactions among processes:* Often a component may require multiple processes to achieve the required form and finish. It is difficult to select processes for various features in the objects without accounting for interaction of costs among different processes. For example consider six different designs shown in Figure 2. The following table lists the processes that should be assigned to different holes based on manufacturing cost.

Table 1: Process Selection Results for Different Designs Shown in Figure 2

Design Index	Process for hole A	Process for hole B	Process for hole C
Design 1	Sand Casting	NA	NA
Design 2	NA	Drilling	NA
Design 3	Drilling	Drilling	NA
Design 4	NA	NA	Sand Casting and Boring
Design 5	Sand Casting	NA	Sand Casting and Boring
Design 6	NA	Sand Casting and Boring	Sand Casting and Boring

Even though hole A has same tolerances in Designs 1 and 3, it has been assigned different processes. Based on the tolerance alone, casting process in adequate to make this hole in both designs. However, casting requires use of cores to make holes and therefore increases the cost of casting process. Combined setup cost and processing cost for drilling a hole is higher then the use of a core in casting process. Therefore, in Design 1 casting is preferred for creating hole A. On the other hand in Design 3, there exists another hole labeled as hole B that requires drilling to meet its stricter tolerance requirements. Therefore a drilling setup cost will be incurred in drilling hole B irrespective of the process assigned to hole A. Based on only the processing cost, drilling is cheaper than casting (i.e., if the part is going to be setup on a drilling machine to create hole B, then making hole A in the same setup costs less compared to the cost of using a core in the casting process to make hole A). Therefore in case of Design 3, drilling is the preferred method of making hole A even though casting can create it.

- *Cost estimation in presence of imprecision*: In embodiment design, there is uncertainty in design parameters. These parameters can be represented as ranges, thereby resulting in ranges on process parameters. Commercial cost estimation systems do not allow imprecision in process parameters. Therefore, the cost estimation step needs to account for such imprecision.

This paper describes a systematic approach and required algorithms to select process and material combinations during the embodiment design stage. Based on the approach and the algorithms described in this paper, we have developed a process and material selection system called WiseProM (Wizard for Selection of Processes and Materials) that can be used by designers during the design embodiment stage. Given design requirements in terms of business, material, and form requirements, this system helps designers in selecting the proper combination of materials and processes to meet design requirements. To reduce the computational effort during the selection process, our system divides the selection into two steps and uses a depth first branch and bound search algorithm. We store process and material knowledge in the following three databases: process database, material database, and process and material compatibility database. These databases are used in selecting suitable materials and generating suitable process sequences. Various promising process and material options are evaluated using a commercial cost estimation system. Our system recommends the least expensive process and material combination to the designer.

WiseProM allows designers to consider a wide variety of process and material options during the embodiment design stage. This allows them to find the most cost-effective combination. By selecting the process and material combination during the design embodiment stage, designers can ensure that the detailed design is compatible with all of the process constraints for the selected materials and processes.

This paper is organized in the following manner. Section 2 describes related research that has been done in the area of material and process selection. Section 3 provides an overview of our approach. Section 4 describes the algorithm used to generate combinations of materials and primary processes to meet design requirements. Section 5 describes the algorithm used to construct alternative process sequences for various shape modification features. Section 6 describes the algorithm for estimating cost associated with a process sequence. Section 7 describes the branch and bound algorithm used to identify the non-dominating process sequences. Section 8 describes detailed cost analysis functions that can be used by the designer to select a combination of a material and a process sequence. Section 9 describes the system implementation and provides two detailed examples. Section compares our system with similar systems and lists limitations of the current system and possible extensions.

2. LITERATURE SURVEY

A wide variety of computational methods have emerged to provide software-aids for performing manufacturability analysis [Gupta et al. 1997]. The majority of manufacturability analysis research is focused toward creating software tools applicable during detailed design. Such systems vary significantly by approach, scope, and level of sophistication. At one end of the spectrum are software tools that provide estimates of the approximate manufacturing cost. At the other end are sophisticated tools that perform detailed manufacturability analysis and offer redesign suggestions. For analyzing the manufacturability of a design, the existing approaches can be roughly classified into two categories. In *direct* approaches [Ishii and Miller 1992, Ishii 1993, Rosen et al 1992, Shankar and Jansson 1993], design rules are used to identify infeasible design attributes from direct inspection of the design description. This approach is useful in domains such as near-net shape manufacturing. In *indirect or plan-based* approaches [Hayes et al 1989, Hayes and Sun 1994, Gupta and Nau 1995, Gupta 1997, Subramanyan and Lu 1991] the first step is to generate a manufacturing plan, and then to evaluate the plan in order to assess the manufacturability of design. This approach is useful in domains where thare are complex interactions between manufacturing operations. Descriptions of representative manufacturability analysis systems can be found in [Beiter and Ishii 1996, Boothroyd 1994, Hayes and Sun 1994, Hu and Poli 1997, Gupta 1997, Ishii and Miller 1992, Ishii 1993, Mahajan et al 1993, Shah et al 1990, Shankar and Jansson 1993, Subramaniam and Ulrich 1994, Warnecke and Bassler 1988, Lam 1995, Gupta et al 1995, Minis et al 1999, Herrmann et al 1996]. Analysis based systems are a step in the right direction and leading to cost savings.

In the last decade, we have witnessed considerable research in the area of extending manufacturability considerations into early design stages [Cogun 1994, Grosse and Sahu 1994, Mahajan et al 1993, Mukherjee and Liu 1997]. Below we summarize four systems.

- Ashby et al [Ashby and Easwi 1999] have developed a commercial software called Cambridge Engineering Selector (CES). It includes about 3,000 materials and 125 processes in its database. Designers can input desired ranges of parameters by graphical or textual interface and use normalized design requirements [Ashby 1992]. The CES system uses database search techniques to locate the suitable combination of processes and materials. Each process in the CES database has a parameter that states whether it is a primary, secondary or tertiary process. However, the designer needs to manually select the process sequence.

- Kunchithapatham [Kunchithapatham 1996] has developed a Material and Process Advisory System. This system includes 42 materials and 17 processes in its database. It has three databases: Materials Database, Process Database and Material and Process Compatibility Database. Rather than storing the actual values of various material and process parameters, material and process data are stored using three levels: high, medium and low. This system does not incorporate specifics of shape in material and process selection.

- Smith [Smith 1999] has developed a web based material process advisory system. It is a Java Applet running on the Internet. It includes 16 materials and 22 processes. Designer can only input one number for each design parameter. This system incorporates shape in the process selection. It provides process sequence, but the designer should input new parameters for special features after choosing the primary process and the material. Results are ranked based on the matches between data in the database and design parameters. This system does not use detailed cost model to rank results.

- Feng et al [Feng and Zhang 1999] have developed a Conceptual Process Planning system at Manufacturing Engineering Laboratory of NIST. It loads design data from a data file that includes material specification, quantity, main shape, feature types, tolerance requirements on features, and dimensions of the workpiece. This program selects a process based on predefined shape-process, feature-process and material-process tables. It also includes a cost model to estimate manufacturing cost.

A detailed comparison of these systems with the system described in this paper is given in Section 10.2. Apart from the four systems described above, there exist other systems for material and process selection, such as CAMPS (Computer Aided Material/Process Selection) [Bock 1991], OSPAM [Lam 1995] and MAMPS (Material and Manufacturing Process Selection) [Giachetti 1998].

3. BACKGROUND AND OVERVIEW

3.1 Definitions

This section describes basic definitions that are needed to describe our process and material selection approach in the following sections.

- ***Cost Interval:*** Due to imprecision in the design requirements, it is not possible to assign exact parameters to processes (e.g., diameter of hole) and material (e.g., weight of material) in a material and process sequence. Therefore it is not possible to exactly compute cost associated with a sequence. Instead cost interval is used to describe the minimum and maximum cost associated with a sequence due to imprecision in design parameters.

- ***Total Production Cost:*** Total production cost C for a sequence s is defined as:

$$C(s) = C_M + \sum_{i=1}^{n} C_{Pi} + \sum_{i=1}^{n} C_{Ti} + \sum_{i=1}^{n} C_{Si}$$

  where C_M is material cost, C_{Pi} is the processing cost associated with the i^{th} process in the sequence (it includes both labor and capital cost), C_{Ti} is tooling cost with the i^{th} process in the sequence, and C_{Si} is setup cost with i^{th} process in the sequence. If there is any imprecision in design requirements, then the cost is defined by a cost interval.

- ***Dominated and Dominating Sequences:*** Let s be a sequence. We denote the minimum cost associated with s by $C_{min}(s)$ and the maximum cost associated with s by $C_{max}(s)$. Please note that $C_{max}(s) \geq C_{min}(s)$. A sequence *s''* dominates another sequence *s*, if and only if: $C_{max}(s'') \leq C_{min}(s)$. This condition implies that despite imprecision, the worst possible outcome for sequence *s''* due to imprecision is still better than or comparable to the best possible outcome for sequence *s*. Therefore, we can always prefer *s''* over *s*. In Figure 3, sequence *s''* dominates sequence *s*. But *s''* does not dominate sequence *s'*, because the cost interval for these two sequences intersect.

- ***Material Requirements (R_M)*:** These requirements are stated in terms of required ranges of material parameters. The complete list is shown below:

  - Density
  - Elastic limit/density
  - Fracture toughness/density
  - Young's modulus/density
  - Hardness
  - Melting point
  - Specific heat
  - Resistivity
  - Solvent Resistance

  As indicated in the above list, we use three parameters that are normalized with respect to density. First, we use normalized elastic limit (e.g., elastic limit/density). A part's load sustaining ability is directly proportional to its size. However, increasing size will also increase material cost. Materials that can provide high strength with reasonable component size can be considered to have high structural efficiency. Hence we need to search materials that provide the desired structural efficiency [Magrab 1997]. Therefore, we use a normalized elastic limit to select material with specified structural efficiency. Second, we use normalized fracture toughness. For the same reason as stated above, normalized fracture toughness (e.g., fracture toughness/density) should be used to search materials. Finally, we use normalized

Young's modulus (e.g., Young's modulus/density) to search materials with specified stiffness efficiency [Magrab 1997].

- ***Business Requirements (R_B)*:** These requirements are stated in terms of ranges on required tooling lead-time, production rate, and overall production quantity. Here the term tooling lead-time means the time needed to create and/or procure tooling to start production, and the term production rate means the units produced per week.

- ***Form Requirements (R_F)*:** These requirements are stated in terms of gross shape and shape modification features. In addition to geometric information, gross shape and shape modification features also include tolerance and surface finish information. There are two different levels: (1) high level, (2) detailed level.

  - *High Level Form Requirements:* At this level we currently only use envelop size.
  - *Detailed Form Requirements*: These are expressed using one gross shape and zero or more shape modification features. For gross shapes we have two types of parameters. The first class of parameters is common to all gross shape types. The second class of parameters is specific to each gross shape type. The common gross shape parameters are: (1) gross shape name, (2) gross shape type, (3) tolerance, (4) surface roughness, (5) number of plane faces, and (6) number of curve faces. Details of specific parameters are different for different gross shape types, but they are all dimensional parameters. Various gross shape types considered in our current system are shown in Figure 4. Our gross shape types are similar to the ones described in [Ashby and Easwi 1999]. For shape modification features we also have two types of parameters: common and specific. The common shape modification features are: (1) number of features, (2) feature name, (3) feature type, (4) tolerance, (5) surface roughness, (6) number of plane faces, (7) number of curve faces, and (8) manufacturing direction. Details of specific parameters are also different for different shape modification feature types. Various shape modification feature types considered in our current system are shown in Figure 5.

3.2 Process and Material Information Models

In order to perform process and material selection using a software system, we need to model the required information about processes and material. Our process and material information models are similar to the ones described in [Feng and Song 2000a, Feng and Song 2000b].

Both materials and processes can be classified hierarchically. Figure 6 and 7 show these hierarchies. Usually decisions that deal with the selection of specific instances of process are made during the process planning stage. On the other hand, decisions that deal with the selection of specific instances of materials are made during the detailed design stage. Therefore, in our information models, we do not store information about material and process instances. Rather, we store information about material and process classes.

Our current material information model consists of the following eleven mechanical, thermal, and environmental properties: (1) material type, (2) material subtype, (3) material name, (4) density, (5) elastic limit, (6) fracture toughness, (7) Young's modulus, (8) hardness, (9) ductility, (10) Poisson's ratio, (11) melting point, (12) specific heat, (13) resistivity, and (14) solvent resistance. Our material information model has been implemented using a relational database. Currently it contains 52 material classes.

Many mechanical components are produced using a sequence of processes, involving more than one process. Therefore the processes used to manufacture a mechanical product can also be classified into four types. *Primary processes* are net-shape processes such as casting, forging, and injection molding. These processes are used to produce the gross shape of a part. *Secondary processes* are shape modification feature creation processes, such as machining and electro-discharge machining. *Tertiary processes* are feature finishing operations (i.e., processes that do not affect gross part and feature geometry) such as grinding, reaming, and lapping. Finally, *surface treatment processes* do not alter the geometry but change the material properties. Examples of surface treatment processes include quenching, annealing, and tempering. Our current work does not include surface treatment processes.

The shape of a part has a major bearing on the process selected to produce it. Flat parts with thin cross sections cannot be cast properly. Very complex parts cannot be manufactured by machining economically, whereas they may be easily cast or molded. So different manufacturing processes vary in their limitations on the shapes produced. As described above, a part can be composed of one gross shape and zero or more shape modification features. For each process we model its shape producing capabilities.

Size or dimension limits can be important considerations in selecting a process. Generally, the maximum size that can be produced by any one given process is often limited simply by the size of available equipment. In some processes, there are limitations due to process conditions themselves. More frequently, processing techniques are limited in their capacity to produce small size, especially minimum wall thickness. The wall thickness of a casting may be limited by the fluidity of metal. Therefore, very thin, very small, or very large components usually can be made only under special circumstances and at an extra cost. Tolerance and surface roughness requirements also determine which process can be used. Therefore, we model tolerance and surface roughness capabilities of various processes in our system.

Production quantity is another significant factor that plays an important role in process selection. For example, if we choose a process that requires a reusable custom tool such as hot chamber die- casting, it will only be suitable for a large quantity production run. Some processes have pre-condition requirements. For example, consider broaching. If it is used to manufacture an irregular hole, it requires a preexisting opening in the part. Boring also requires an existing hole as a precondition for its use.

Our process information model consists of the following: (1) process type, (2) process name, (3) production quantity, (4) production rate, (5) tool lead-time, (6) gross shapes types supported, (7) shape modification features types supported, (8) manufacturing direction, (9) tolerance, (10) surface roughness, (11) process precondition requirement type, (12) precondition requirement, (13) precondition processes, (14) dimensions which are different for different processes, generally it includes (15) length, (16) width, (17) height, and (18) thickness. Our process information model has been implemented using a relational database. Currently it contains 31 processes. In the process information model the term tooling lead-time means the time needed to create and/or procure tooling to start production.

Material properties directly influence the production methods. The selection of material must be closely coupled with the selection of a manufacturing process. For example, plastics can be molded, but cannot be forged; steels can be cast or forged, but cannot be vacuum formed. As an example, consider molybdenum titanium alloy. It is a refractory material with high hardness. If we want to manufacture a small hole, cavity-type EDM is the process to be used instead of drilling. Compatibility among processes and materials is modeled using a material process compatibility model. Material and process compatibility model consists of the following fields: process name, material name, and compatibility status (Yes or No). Figure 8 shows relationship between process and material information models graphically.

3.3 Overview of Process and Material Selection Approach

Our approach to process and material selection consists of the following steps:

- *Step 1. Generating Combinations of Materials and Primary Processes*. In this step, based on the material requirements, business requirements, and high-level form requirements, we generate combinations of primary processes and materials that can meet these requirements. Section 4 describes our algorithm for this step in detail.

- *Step 2: Finding Promising Process Sequences by Adding Secondary and Tertiary Processes into Various Combinations of Materials and Primary Processes.* For each primary process and material combination that meets the first level of design requirements, we do the following:

    - *Step 2a: Adding Detailed Form Requirements*. We add detailed form requirements in terms of gross shape and shape modification features to the combination. Such form requirements need to be consistent with the constraints imposed by the primary process on the gross shape.

    - *Step 2b: Constructing Process Sequences for Various Shape Modification Features and Gross Shape*. Once the detailed form requirements have been defined for a combination, we start constructing alternative process sequences for various shape modification features. Section 5 describes our algorithm for this step in detail.

    - *Step 2c: Finding Non-Dominated Sequences*. Based on the cost considerations we first prune unpromising process sequences for shape modification features. Section 6 describes how the cost is estimated for a given sequence. Then, we perform a depth first branch and bound search to find all non-dominated sequences from the remaining alternatives. Section 7 describes the branch and bound algorithm in detail.

- *Step 3: Selecting Material and a Process Sequence.* At this step, the designer can analyze various non-dominated sequences and a detailed comparison on the cost can be performed. Dominance among different sequences can be determined at even narrower levels and a final decision can be made by the component designer. Section 8 describes this step in detail.

4. GENERATING COMBINATIONS OF MATERIAL AND PRIMARY PROCESSES

This section describes the algorithm used to generate a set of combinations of material and primary processes C_{mp} that can satisfy business requirements, material requirements, and high-level form requirements. Various steps in our algorithm are described below:

- *Step 1:* Search through material database to find materials that can meet all material requirements and store them in set M. More details on this step are given later in this section.

- *Step 2:* If set M is not empty, then for each material m in set M, search through the process database to find a set of processes P_p that are: (1) primary processes, (2) compatible with material m, and (3) meet all business and high level form requirements. More details on this step are given later in this section. For every p in P_p, add the material and primary process combination (p, m) into set C_{mp}.

- *Step 3:* Show all combinations in set C_{mp} to the designer. Designer can select a maximum of ten combinations that are going to be used during the second level selection.

As described above, we first choose materials to meet all Material Requirements (R_M). Requirements for each material attribute are expressed in terms of a range (U_S, U_B). The material information model also stores ranges (D_S, D_B) associated with every material. As shown in Figure 9, there are two types of search possible for every attribute:

1. *Contained:* $U_S \geq D_S$ and $U_B \leq D_B$

   This type of search implies that the complete range of requirement on the material attribute can be met by the entry in the database (i.e., the entry in database will work for the entire range).

2. *Intersection:* $D_S \leq U_S \leq D_B \leq U_B$ or $U_S \leq D_S \leq U_B \leq D_B$

   This type of search implies that at least one point in the specified range of requirement on the material attribute can be met by the entry in the database (i.e., the entry in database will have at least one point).

To provide designer more material choices, we support the intersection type of search.

Our algorithm for finding all suitable materials (M) is described below:

1. Initialize set M as an empty set.

2. Choose a material *m* from material database that has not been considered so far. If no such material exists, then return *M*.

3. Compare value of each material attribute with the corresponding attribute in the material requirements (if designer didn't input value for this attribute, it means that this attribute isn't under consideration, hence go to the next attribute). If any attribute cannot meet the requirement, go back to Step 2. If it can meet the requirement of all attributes, then go to Step 4.

4. Add material *m* into material set *M* and Go to Step 2.

Our algorithm for finding all suitable primary processes P_p for a material *m* is described below:

1. Initialize set P_p as an empty set.

2. Choose a process *p* from process database that has not been considered before. If no such process exists, then return P_p.

3. Check whether *p* is compatible with material *m*. If not, go back to Step 2.

4. Compare value of each business attribute and high level form attribute with the corresponding attribute in the business and high level form requirement (if designer didn't input value for this attribute, it means that this attribute isn't under consideration, hence go to the next attribute). If any attribute cannot meet the requirement, go back to Step 2. If it can meet the requirement of all attributes, then add it to Set P_p.

5. CONSTRUCTING SETS OF ALTERNATIVE PROCESS SEQUENCES FOR SHAPE MODIFICATION FEATURES AND GROSS SHAPE

This section describes the algorithm used to generate a set of alternative process sequences for each shape modification feature and gross shape's unfinished accuracy requirements.

For each combination of material and primary process, designers need to define one gross shape and zero or more shape modification features to express detailed form requirements. Before we construct alternative process sequences, we need to make sure that the primary process is consistent with the gross shape. The algorithm for doing this is given below:

- *Step 1:* Identify what design requirements can be reached by primary process p_p using the following steps:
  - Check whether p_p can manufacture this type of gross shape and can meet the dimension requirements. If not, go to Step 3. While checking whether process p_p can meet the dimension requirement, search type "contained" is used (i.e., the input value range of each dimension parameter should be contained in the corresponding value range of p_p).

- Check whether p_p can also reach gross shape's accuracy requirements. While checking whether process p_p can meet the accuracy requirement, search type intersection is used. Go to Step 2.

- *Step 2:* If both dimension and precision requirements are reached, shape modification feature's current accuracy level is also updated and is set equal to gross shape's accuracy level. If only dimension requirements are reached, then update gross shape's current accuracy to primary process's capability.

- *Step 3:* Show corresponding error information to the designer, who can either change design requirements or delete this combination from the combination list.

The available process options for shape modification features and gross shape's unfinished accuracy requirements can be modeled as a process option forest, where, each process option tree *T(N, E)* in the forest describes either the process sequence options for a shape modification feature, or the gross shape's unfinished accuracy requirements. Various edges *E* represent various processes and various nodes *N* represent the list of unfinished form requirements with current accuracy information. We define each process option tree using a forward chaining scheme.

First we generate a process option tree for the unfinished accuracy requirements for the gross shape. If accuracy requirements are not met then various alternative processes for meeting the unfinished requirements are added to the process option tree.

If all gross shape's form requirements can be reached, then every shape modification feature's current accuracy level is also updated and set equal to the accuracy level of the gross shape. For shape modification features, each root node contains the shape modification feature's form requirements. Various processes that can meet these requirements are considered and if found feasible added into the option tree. Secondary processes are used to manufacture shape modification feature, secondary process selection begins with the retrieval of all secondary processes generally associated with the design. Then appropriate processes are selected for the shape modification feature and are assessed for global feasibility and their compatibility with the primary process. Sometimes the primary process used to manufacture the gross shape can also be used to manufacture the shape modification feature, such as milling, sand casting, injection molding. Under such conditions, the primary process is also considered as a possible choice for creating various shape modification features. Tertiary processes are used to satisfy surface finish requirements for shape modification features that require more accuracy than that can be provided by the feasible primary and feasible secondary process. For every secondary process with unfinished tolerance/surface requirement, tertiary process nodes are created and appropriate tertiary processes are selected for the remaining tolerance/surface finish requirements. Leaf nodes contain no requirements. Hence they correspond to the finished feature. Figure 10 shows a portion of a process option tree for a shape modification feature.

The detailed algorithm to construct the process option tree for a shape modification feature is described below:

- *Step 1:* Use recursive algorithm TREE(*R, n*) to construct the process option tree by setting R to be the form requirement for the feature and *n* to be the root node in the forest (i.e., a set of trees) corresponding to this shape modification feature.

- *Step 2:* Convert the tree into set of sequences *S* using tree traversal method [Cormen et al. 1990]. The number of sequences is equal to the number of leaf nodes in the tree.

Let *R* be a set of form requirements for a feature. Algorithm TREE(*R, n*) is described below:

Algorithm TREE(*R, n*)

- If *R* is empty, then return.

- Otherwise, do the following:

  - Find the set of processes *P* that can satisfy one or more requirements in *R* (Detailed steps are described later).

  - If *P* is empty then return.

  - Otherwise for every *p* in *P*, then do the following:

    - Add a node *n'* corresponding to the requirements left after using *p* on *n*.
    - Store remaining unfinished requirements in *R'*.
    - TREE(*R'*, *n'*).

The algorithm for finding the set of processes that can satisfy one or more requirements in *R* is described below:

- *Step 1:* Initialize *P* as an empty set.

- *Step 2:* Select a process *p* from the database that has not been considered before. If no such process exists then return *P*.

  - Check if *p* is compatible with the material *m* associated with node *n*, if it is not compatible, then go to Step 2.

  - Check the following two conditions for *p*:

    - If there is a dimension requirement that has not been reached at *n*, then check if *p* is a secondary process or the primary process associated with the combination.
    - If there is accuracy requirement left, then check if *p* is a tertiary process.

  - If the above conditions are not satisfied then go to Step 2.

- Otherwise, do the following:

    - Test the following two conditions:

        - Check whether *p* can be used to manufacture shape modification feature's feature type.
        - Check the shape modification feature's dimensional parameters with corresponding values in the process database. Use search type "contained (i.e., the input value range of each dimension parameter should be contained in the corresponding value range of *p*).

    - If the above two conditions are met then add *p* to *P*. Otherwise go to Step 2.

6. ESTIMATING COST FOR PROCESS SEQUENCES

This section describes our approach to estimating cost interval ($C_{min}(s)$, $C_{max}(s)$) for a given sequence *s* using SEER-DFM cost estimation system.

SEER-DFM is a commercial system to analyze costs associated with manufacturing, as well as other life-cycle factors [Galorath 1999]. SEER-DFM system requires exact specifications of the process parameters for estimating cost. Due to imprecision in design parameters, we also have imprecision in the process parameters. Therefore, rather then estimating a single cost number, our approach is to obtain a cost interval. However, we cannot directly call SEER-DFM to estimate a cost interval. We usually need to make multiple calls to the cost estimation system, each call with completely specified set of parameters by selecting specific value of parameters in the parameter range. Each call results in a single cost estimate. By appropriately sampling the entire parameter ranges, and making calls to cost estimation system, we estimate the cost interval. Since each call to the cost estimation system is computationally expensive, we would like to estimate the cost interval with the minimum number of calls to the cost estimation system. Section 6.1 describes our approach for this problem.

Calling SEER-DFM and getting the cost estimation results is a time consuming step. We need to estimate cost of many different processes. Therefore whenever possible we try to cache the previously estimated cost. Section 6.2 describes our approach.

6.1 Computing Cost in Presence of Imprecision in Deign Parameters

To estimate the maximum cost and the minimum cost, we need to first identify the values of process parameters that will lead to the maximum and minimum cost values. When process parameters are independent and have a monotonic effect on cost, interval estimation is relatively straightforward. This can be accomplished by making only two calls to the cost estimation system. Section 6.1.1 describes our approach for cost estimation in such cases. When process parameters are dependent, estimating cost interval involves more sophisticated reasoning. Section 6.1.2 describes our approach for cost estimation in such cases.

In order to develop a systematic approach for making calls to the cost estimation system, we need to first understand what kind of effect various process parameters will have on the final cost. By performing a systematic study of the SEER-DFM system, we have identified the nature of relationship between various process parameters and the final cost. The relationship between each process parameter and the final cost in SEER-DFM is monotonic. Relationships between process parameters and final cost can be classified into the following two types:

- the final cost of using this process decreases as the value of process parameter increases ("↓").
- the final cost of using this process increases as the value of process parameter increases ("↑").

6.1.1 Estimating Cost When Process Parameters are Independent

We make two calls to SEER-DFM system to estimate cost interval when process parameters are independent. Let X be the set of process parameters. For each parameter $x \in X$, the following approach is used to decide which value of the parameter will be used in estimating the cost.

- If the relationship between parameter x and final cost is "↓":
    - Minimum value of x is used to estimate the maximum cost.
    - Maximum value of x is used to estimate the minimum cost.
- If the relationship between parameter x and final cost is "↑":
    - Minimum value of x is used to estimate the minimum cost.
    - Maximum value of x is used to estimate the maximum cost.

We make two calls to the cost estimation system. The first call is made for estimating the maximum cost and the second call is made for estimating the minimum cost.

6.1.2 Estimating Cost Range in Presence of Dependent Process Parameters

When process parameters are dependent we need another method to determine the parameters values to estimate the maximum and the minimum cost. For example, among the input parameters needed for the cost estimation of process milling, finished weight and removed weight are dependent parameters, because the sum of these two parameters is a constant.

Let C be the processing and material cost for a given process. Let us assume that x_1 and x_2 are two process parameters that are mutually dependent. Now C can be modeled as:

$$C = a_1 x_1 + a_2 x_2 + a_0$$

Now, due to dependency between x_1 and x_2,

$$x_2 = b_2 x_1 + d_2$$

The value range of x_1 is: $x_1^{\min} \le x_1 \le x_1^{\max}$

We need to get values of x_1 and x_2 for computing the maximum and minimum cost.

Our algorithm to compute this is as following:

1. Replace x_2 in the cost equation with x_1 and we get:
$$C = (a_1 + a_2 b_2) x_1 + a_2 d_2 + a_0$$

2. If $a_1 + a_2 b_2 > 0$,
   $\left(x_1^{\max}, b_2 x_1^{\max} + d_2\right)$ is the value set to get maximum cost.
   $\left(x_1^{\min}, b_2 x_1^{\min} + d_2\right)$ is the value set to get minimum cost.

   If $a_1 + a_2 b_2 < 0$,
   $\left(x_1^{\min}, b_2 x_1^{\min} + d_2\right)$ is the value set to get maximum cost.
   $\left(x_1^{\max}, b_2 x_1^{\max} + d_2\right)$ is the value set to get minimum cost.

So far we have only discovered a linear dependency between at most two parameters. However, our scheme can be easily extended to cost estimation situations where dependency may exist between multiple parameters and such dependency may be non-linear in nature. To discover dependency constraints, a design of experiments approach can be used, by treating the cost estimation system as a black box. Various combinations of input parameter values can be used to generate the input set for the cost estimation system and its output can be analyzed to determine if there are dependencies in the input parameters. Once a suitable expression of dependency is identified, an analytical approach similar to the one outlined above can be used to find the appropriate setting of input parameters to compute the cost interval.

6.2 Caching Cost Estimation Results from Previous Sequences

Whenever a new edge is inserted into the process option tree, we need to calculate the cost associated with the process that results in this edge. For a given feature we may need to consider the same process many different times at different levels in the tree. Typically it takes 3 seconds for SEER-DFM to estimate the cost for one node, making it computationally intensive. Therefore, we use the following techniques to reduce the cost estimation time:

1. If cost interval has already been computed for a process and shape modification feature combination, then cache the cost interval rather then recomputing it. We make use of a unit cost interval (i.e., cost interval for one shape modification feature) during caching. To get the cost for multiple features we simply multiply the unit cost by the number of features.

2. Divide the cost interval ($C_{min}(s)$, $C_{max}(s)$) into two different cost interval components, sharable $(C_{\min}^{s}(s), C_{\max}^{s}(s))$ and non-sharable $(C_{\min}^{ns}(s), C_{\max}^{ns}(s))$.

$$C_{\min}(s) = C^{s}_{\min}(s) + C^{ns}_{\min}(s)$$
$$C_{\max}(s) = C^{s}_{\max}(s) + C^{ns}_{\max}(s)$$

As described in section 3.1, each process has three costs associated with it: setup cost, tooling cost and processing cost. Among these costs the tooling and the processing costs are not sharable. Setup cost is sharable. If, in a sequence two or more processes use the same setup then setup cost is only incurred once. Hence, it is shared between these processes. But tooling and processing costs are not sharable. Breaking up the cost into sharable and non-sharable components increases the caching efficiency by creating more caching opportunities.

For different processes, methods to calculate tooling and processing costs are different. For processes belonging to machining, such as turning and milling, we can easily estimate the unit cost of making a feature using SEER-DFM. But for processes belonging to casting/molding, computing the unit cost for making a feature is more complex using SEER-DFM. For example, let us assume that we need to calculate the tooling and processing cost associated with the sand casting process to manufacture a cylindrical hole. To compute this we first need to estimate the tooling and processing cost of process sand casting to manufacture the part with no hole. Then, we estimate the tooling and processing cost of process sand casting to manufacture part with one hole. The difference between them gives the tooling and processing cost of process sand casting to manufacture the hole.

7 FINDING NON-DOMINATED SEQUENCES

We use a depth first branch and bound search algorithm to explore various options and identify a set of non-dominated solutions in a computationally efficient manner. Details on various search algorithms can be found in [Sriram 1997]. In presence of imprecision, we cannot use the classical branch and bound algorithm that just stores the current best solution. Instead, we need to store the set of non-dominated solutions. A sequence is considered as a part of the *current set of non-dominated solutions*, if so far during the search no other sequence has been found that dominates any solution in this set.

Let S_{ND} be the set of current non-dominated solutions. During the search process, S_{ND} will have the following properties:

1. For every sequence s in S_{ND}, there is no other sequence s' in S_{ND} such that $C_{min}(s')$ is greater than $C_{max}(s)$.

2. For every sequence s in S_{ND}, there is no sequence s' in S_{ND} such that $C_{max}(s')$ is lower than $C_{min}(s)$.

The branch and bound algorithm proceeds in the following manner. Let s'' be a new sequence (either partial or full) being considered during the search. During the search process, s'' is handled in the following manner:

1. If there is one s' in the set of the current non-dominated solutions S_{ND} that dominate s'', then s'' is pruned.

2. If s'' is a complete sequence and there is at least one s in the set of current non-dominated sequences S_{ND} such that $C_{min}(s'')$ is smaller than $C_{max}(s)$, then s'' is added to the set of current non-dominated solutions. If s'' is added to the set of current non-dominated solutions S_{ND}, then we examine S_{ND} to make sure that it still satisfies the two conditions described above. If after inserting s'' into S_{ND} any solution in S_{ND} is dominated by s'', then we remove the dominated solution from set S_{ND}.

The depth first branch and bound algorithm is initialized by setting the current non-dominated set as an empty set. Then dominated sequences belonging to each feature are pruned. Then a recursive algorithm EXPAND, is called to actually construct and evaluate the option space. Algorithm INITIALIZE that initializes the search is described below:

Algorithm INITIALIZE(F)

- Initialize the set of current non-dominated solution S_{ND} to a null set.

- Initialize set of unfinished features F to include all shape modification feature f_i ($i \in (1, K)$), K is the number of shape modification features.

- For each f_i in F,

    - Let S_{fi} be the set of sequences available to create f_i. For each s in S_{fi} do the following:

        - If s is dominated by a sequence s' in S_{fi}, then do the following:

            - If s does not includes any setup sharable step, then prune s.
            - If s' includes the same setup sharable steps as s, then prune s.

- Initialize the current hybrid sequence s (union of sequences for individual shape modification features being considered) to be a null set.

- Call EXPAND (F, s)

Details of algorithm EXPAND are described below:

Algorithm EXPAND(F, s)

- Evaluate both sharable and not-shareable cost intervals for s. If s is empty, both minimum and maximum values are set 0.

- If F is empty, then do the following:

- If s is not dominated by any sequence in current non-dominated sequences S_{ND}, then insert s into S_{ND}
- Otherwise, return

- Otherwise, do the following:
  - Compute the lower bound of cost C_l *(F)* for *F*. $c_{\min}^{ns}(s_f)$ is the minimum non-sharable cost value for sequence s_f.

$$C_l(F) = \sum_{f \in F} \min_{s_f \in S(f)} (c_{\min}^{ns}(S_f))$$

  - If interval $(C_{max}(s) + C_l(F), C_{min}(s) + C_l(F))$ is dominated by current non-dominated set S_{ND}, then return.
  - Otherwise, do the following:
    - Pick a feature *f* in *F* that has smallest number of sequences associated with it.
    - For every sequence s_f for *f*, calculate the cost $C_s(s_f)$ associated with s_f by allowing maximum possible setup sharing using equation $C_s(s_f) = \sum_{i=1}^{n} C_{\min}^{ns}(p_i) + \sum_{i=1}^{n} \delta_i \cdot C_{\min}^{s}(p_i)$. Rank them in the increasing order and select s_f with minimum cost and do the following:
      - EXPAND (F-f, $s \cup s_f$)

We believe that the effectiveness of our algorithm will depend on how tightly various parameters can be defined during the embodiment design stage. If parameters have very large ranges, then we believe that very few solutions will dominate other solutions and the pruning conditions will not work very effectively.

8. SELECTING MATERIAL AND A PROCESS SEQUENCE

After a set of non-dominated solutions has been found, we provide four detailed cost analysis utilities to help designers select a combination of a material and a process sequence. These utilities are described below:

- *Comparison of Cost Interval of Selected Sequences*: Show comparison of cost interval ($C_{min}(s)$, $C_{max}(s)$) in selected sequences. This utility can be used by the designer to identify more promising among the set of non-dominated sequences.

- *Pair-Wise Comparison of Cost:* After a set of non-dominated solution has been found, designer can proceed with the pair-wise analysis of the solutions. At this stage we try to find out if the structure of the cost equation is such that one solution in the pair will be dominate the other solution for all values of the uncertain parameter in the given range. To simplify visualization, we have combined various forms parameters into three main parameters that influence the final cost: shape complexity, dimension and precision. The quantity is used as the fourth main parameter. Each parameter has five value levels. Designer can select one attribute to study the local dominance relationship, setting all other three to specific value levels. We remove locally dominated solutions from the set of non-dominated solutions. The remaining solutions can be further examined by the designer. If the designer tightens the bounds on some parameter, then we reevaluate solutions and remove the solutions that are dominated.

- *Cost Decomposition of a Sequence:* This utility can be used to study various components of cost for a sequence. It includes material, setup, tooling, and processing cost for primary process; and setup, tooling, and processing cost for each secondary and tertiary process. Designer can use this utility to study a sequence in more detail and see how changes in an imprecise parameter influence various cost components.

Finally, the designer can assign a probability distribution function with each of the uncertain parameter (i.e., parameter range). At this stage, the designer can proceed with computing the expected value of production cost for each non-dominated sequence, and finally select the sequence that has the lowest value of expected production cost.

9. DESCRIPTION OF IMPLEMENTATION AND EXAMPLES

Our system has been implemented using Java. All databases are maintained in Microsoft Access. A designer can use a browser to connect to our server. Browser automatically downloads the Java program, and it runs in the browser. We use SEER-DFM cost estimation software to estimate the cost associated with various material and process sequences. Figure 11 shows our system architecture.

As described below our system is based on an open architecture and can be easily updated and reconfigured:

1. It is easy to include new materials or processes. System reads materials, processes information through data files that are automatically generated by Microsoft Access. When a system administrator needs to add new materials or processes from, she/he can update the database stored in Access and export new data files, containing information about new materials and processes.

2. It is easy to edit gross shape types and shape modification feature types. The system makes use of two definitions files: gross shape types file, and shape modification feature types file. By editing these files and incorporating appropriate changes in the process information model, the system can work with an expanded set of gross shapes and shape modification features.

3. It is easy to adjust the complexity coefficients. We use SEER-DFM to do cost estimation. SEER-DFM requires selecting proper complexity coefficients for correct cost estimation. We provide a file for each process cost estimation model to include all complexity coefficients. This allows us to reconfigure the cost estimation system easily.

In our system, for each main task, a new window is used to get information from the designer and show results to the designer. Figure 12 shows the relationship among all windows used in this system. The following steps describe a typical sequence in which various windows appear during our systems operation:

- “Main Frame” window (Shown in Figure 13) appears when a designer uses a browser to connect to our server. This window is used to carry out all top level functions.

- “Generate Combinations of Materials and Primary Processes” window (Shown in Figure 14) appears when a designer selects “Generate Combination of Materials and Primary Processes” task in the “Main Frame” window. This window is used to specify high-level form requirements, business requirements, and material requirements. Using this information, the designer can generate a set of combinations of materials and primary processes that meet these requirements. Designers can transfer a maximum of 10 combinations from this level to the next level.

- “Generate Process Sequences” window (Shown in Figure 15) appears when a designer selects “Generate Process Sequence” task in the “Main Frame” window. This window is used to select a material and primary process combination, specify detailed form requirements, and generate non-dominated sequences for the combination.

- “Specify Form Parameters” window (Shown in Figure 16) appears when a designer selects a combination in the window “Generate Process Sequences”, and then selects “Specify Form Parameters” task. This window is used to specify form parameters and it also allows addition of secondary and tertiary processes for various shape modification features.

- “Specify Gross Shape” window (shown in Figure 17) appears when a designer selects “Specify Gross Shape” or “Edit Gross Shape” task in the window “Specify Form Parameters”. This window is used to specify gross shape form parameters.

- “Specify Shape Modification Features” window (shown in Figure 18) appears when a designer selects “Specify Shape Modification Features” or “Edit Shape Modification Features” task in the window “Specify Form Parameters”. This window is used to specify shape modification features.

- “Analyze Cost of Sequences” window (shown in Figure 19) appears when a designer selects “Analyze Cost of Sequences” task in the “Main Frame” window. This window is used to show the sequence details, the cost decompositions, the cost comparisons, and the cost graphs.

- “Sequence Detail” window (shown in Figure 20) appears when a designer selects a particular sequence and select “Show Sequence Detail” task in the window “Analyze Cost of Sequences”. This window is used to show details of the selected sequence.

- “Show Cost Decomposition” window (shown in Figure 21) appears when a designer selects a particular sequence and selects “Show Cost Decomposition” task in the window “Analyze Cost of Sequences”. This window is used to specify the value levels for four cost attributes and to show cost decomposition graphs.

- “Cost Decomposition Chart” window (shown in Figure 22) appears when a designer selects “Show Cost Decomposition Chart” task in the window “Show Cost Decomposition”. This window is used to show cost decomposition charts.

- “Show Cost Comparison” window (shown in Figure 23) appears when a designer selects “Show Cost Comparison” task in the window “Analyze Cost of Sequences”. This window is used to show cost comparison charts.

- “Show Cost Graph” window (shown in Figure 24) appears when a designer selects two sequences and selects “Show Cost Graph” task in the window “Analyze Cost of Sequences”. This window is used to select the parameter that will be varied, set values for other three parameters, and show cost graphs.

- “Cost Graph Chart” window (shown in Figure 25) appears when a designer selects “Show Cost Graph Chart” task in the window “Show Cost Graph”. This window is used to show cost graph charts.

8.1 Example 1: Housing

Let us consider design of a housing. A rough sketch of its form is shown in Figure 26. Various design requirements for selecting combinations of materials and primary processes are given as follows:

Business Requirements:

- Total Production Value: 500 to 2000

  (We assume remaining parameters of business requirements are not specified)

Material Requirements:

- Density: (6.8, 8.1) $10^3 kg/m^3$

- Elastic Limit/Density: (23, 33) $MPa/(10^3 kg/m^3)$

- Fracture toughness/Density: (1.8, 3.0) $MPa \cdot m^{1/2}/(10^3 kg/m^3)$

- Young's molulus/Density: (14, 23) *GPa/ ($10^3 kg/m^3$)*

  (We assume remaining parameters of material requirements are not specified)

High Level Form Requirements:

- Envelop Size: (3, 5) $10^6 mm^3$

Several material and primary process combinations are generated using this information. We assume that the results transferred to the next level are:

- Combination 1: Grey Cast Iron and End Milling
- Combination 2: Grey Cast Iron and Green Sand Casting
- Combination 3: Zinc Aluminum Alloy and Hot Chamber Die Casting
- Combination 4: Grey Cast Iron and Investment Casting
- Combination 5: Grey Cast Iron and Turning

We assume that for every combination the detailed form requirements are as follows:

- Gross Shape

Gross shape type: 3D Parallel Solid	
Number of Planes: 11	Number of Curve Surfaces: 0
Bounding box length: 220-230 mm	Bounding box width: 120-130 mm
Bounding box Height: 140-150 mm	
Volume: 3.7 – 4.5 ($10^6 mm^3$)	Surface Area: 1.48 – 1.68 ($10^5 mm^2$)
Tolerance: 1-3 millimeter	Roughness: 10-13 micrometer

- Feature 1: inner housing

Feature type: Pocket => Non-cylindrical	
Number of Planes: 5	Number of Curve Surfaces: 0
Bounding box length: 180-190 mm	Bounding box width: 80-90 mm
Bounding box Height: 120-130 mm	Number of features: 1
Volume: 1.73 – 2.22 ($10^6 mm^3$)	Surface Area: 0.91 – 1.07 ($10^5 mm^2$)
Tolerance: 1-3 millimeter	Roughness: 10-13 micrometer

- Feature 2: face

Feature type: Surface finish => flat	
Number of Planes: 1	Number of Curve Surfaces: 0
Bounding box length: 220-230 mm	Bounding box width: 120-130 mm
	Number of features: 1
	Surface Area: 0.93 – 1.55 ($10^4 mm^2$)

Tolerance: 0.2-0.3 millimeter	Roughness: 1-3 micrometer

- Feature 3: hole 1

Feature type: Hole => Cylindrical	
Number of Planes: 0	Number of Curve Surfaces: 1
Bounding box length: 30-32 mm	Bounding box width: 30-32 mm
Bounding box Height: 10-12 mm	Number of features: 4
Volume: 7.07 – 9.65 ($10^3 mm^3$)	Surface Area: 0.9 – 1.2 ($10^3 mm^2$)
Tolerance: 0.03-0.06 millimeter	Roughness: 0.5-0.7 micrometer

- Feature 4: hole 2

Feature type: Hole => Cylindrical	
Number of Planes: 0	Number of Curve Surfaces: 1
Bounding box length: 10-12 mm	Bounding box width: 10-12 mm
Bounding box Height: 16-18 mm	Number of features: 10-14
Volume: 1.26 – 2.03 ($10^3 mm^3$)	Surface Area: 5.02 – 6.78 ($10^2 mm^2$)
Tolerance: 0.5-0.7 millimeter	Roughness: 3-6 micrometer

The following sequence is a sequence in the set of non-dominated sequences:

Material: Grey Cast Iron
Step1: Sand casting: To meet the design requirements of gross shape, feature1.
Step2: Milling: To meet the requirements of feature2.
Step3: Drilling: To create hole1 and hole2.
Step4: Grinding: To meet the precision requirement of hole1.

We calculated the cost for this sequence using the SEER-DFM cost estimation tool. Table 3 shows estimated costs produced by SEER-DFM system.

Table 3: Cost Associated with the Sequence for Example 1

Process	Lower Bound	Upper Bound
Sand casting cost ($)	67.2	99.9
milling cost ($)	10.4	17.6
drilling cost ($)	17.9	70.6
grinding cost ($)	23.9	40.7
total cost ($)	119.4	228.8

If the designer decides to use this sequence, then he should generate the process dependent design based on the process constraints of casting as shown in Figure 27.

8.2 Example2: Wheel

Let us consider the design of a wheel. A rough sketch of its form is shown in Figure 28. Various design requirements for selecting combinations of materials and primary processes are given as follows:

Business Requirements:

- Production Value: 5000 to 15000

  (We assume remaining parameters of business requirements are not specified.)

Material Requirements:

- Density: (2.5, 3) $10^3 kg/m^3$

- Elastic Limit/Density: (46, 76) $MPa/(10^3 kg/m^3)$

- Fracture toughness/Density: (6, 12) $MPa \cdot m^{1/2}/(10^3 kg/m^3)$

- Young's modulus/Density: (23, 34) $GPa/(10^3 kg/m^3)$

  (We assume remaining parameters of material requirements are not specified.)

High Level Form Requirements:

- Envelop Size: (6, 10) $10^4 mm^3$

Material and primary process combinations are generated using this information. We assume that the results transferred to the next level are as follows:

- Combination 1: Cast Aluminum Alloy and End Milling
- Combination 2: Cast Aluminum Alloy and Green Sand Casting
- Combination 3: Cast Aluminum Alloy and Hot Chamber Die Casting
- Combination 4: Cast Aluminum Alloy and Investment Casting

We assume that for every combination the detailed form requirements are:

- Gross Shape

Gross shape type: Cylinder	
Number of Planes: 2	Number of Curve Surfaces: 1
Bounding box length: 65-67 mm	Bounding box width: 65-67 mm
Bounding box Height: 24-26 mm	
Volume: 7.96 – 9.16 ($10^4 mm^3$)	Surface Area: 4.9 – 5.5 ($10^3 mm^2$)
Tolerance: 0.4-0.6 millimeter	Roughness: 1-2 micrometer

- Feature 1: profile

Feature type: Profile => Cylindrical	
Number of Planes: 0	Number of Curve Surfaces: 1
Bounding box length: 40-42 mm	Bounding box width: 40-42 mm
Bounding box Height: 14-16 mm	Number of features: 1
Volume: 1.8 – 2.2 ($10^4 mm^3$)	Surface Area: 1.8 – 2.1 ($10^3 mm^2$)
Tolerance: 0.4-0.6 millimeter	Roughness: 1-2 micrometer

- Feature 2: small pocket

Feature type: Pocket => Non-cylindrical	
Number of Planes: 3	Number of Curve Surfaces: 1
Bounding box length: 18-19 mm	Bounding box width: 12-13 mm
Bounding box Height: 24-26 mm	Number of features: 6-8
Volume: 2.5 – 3.1 ($10^4 mm^3$)	Surface Area: 1.9 – 2.2 ($10^3 mm^2$)
Tolerance: 0.4-0.6 millimeter	Roughness: 1-2 micrometer

- Feature 3: hole

Feature type: Hole => Cylindrical	
Number of Planes: 0	Number of Curve Surfaces: 1
Bounding box length: 10-12 mm	Bounding box width: 10-12 mm
Bounding box Height: 24-26 mm	Number of features: 1-1
Volume: 1.89 – 2.94 ($10^3 mm^3$)	Surface Area: 7.5 – 9.8 ($10^2 mm^2$)
Tolerance: 0.05-0.06 millimeter	Roughness: 0.5-0.7 micrometer

The set of non-dominated sequences includes the following two sequences:

- *Sequence 1*:

  Material: Aluminum Alloy
  Step1: Die casting to meet all design requirements except the precision requirement of the hole.
  Step2: Grinding to meet the precision requirements of the hole.

- *Sequence 2*:

  Material: Aluminum Alloy
  Step1: Investment casting to meet all design requirements except the precision requirement of the hole.
  Step2: Grinding to meet the precision requirement of the hole.

We calculated the cost for this sequence using the SEER-DFM cost estimation tool. Table 4 shows estimated costs produced by the SEER-DFM system.

Table 4: Cost Assocatied with Two Sequences for Example 2

Process	Lower Bound	Upper Bound
Sequence 1: die casting cost ($)	2.7	11.12
Sequence 1: grinding cost ($)	2.16	3.9
Sequence 1: total cost ($)	4.86	15.02
Sequence 2: investment casting cost ($)	3.5	9.2
Sequence 2: grinding cost ($)	2.16	3.9
Sequence 2: total cost ($)	5.66	13.1

If the designer decides to select Sequence 1, then he should generate the process dependent design based on the process constraints of casting as shown in Figure 29.

10. CONCLUSIONS

10.1 Comparison of Our System with Different Material and Process Selection Systems

Figure 30 shows the basic structure of a material and process advisory system. The designer inputs design parameters and the system chooses suitable materials and processes from a material and process database by using a selection algorithm, and then outputs the result. To compare different systems, we have defined the following metrics:

System Level Characteristics:

1. *Web-Compatibility*: Whether the program is designed for using on the Internet.
2. *Number of materials in database*: Number of materials included in database.
3. *Number of processes in database*: Number of processes included in database.
4. *Customization option*: Whether designer can customize the database.

***Nature of Input*:**

- *How input is defined*: Whether the data is inputted as a single value, a range (defined by two values), or a qualitative description

***Nature of Output*:**

1. *Single processes/process sequence*: Whether the output is single process or a process sequence.
2. *Cost report*: Whether the system can give cost report on material cost, setup cost, labor cost and other cost components.
3. *Ranking*: Whether the output can be ranked using some scheme.

***Nature of Material and Process Selection Algorithm*:**

1. *Algorithm*: What selection algorithm is used. For example database search and branch and bound are different search algorithms.
2. *Amount of Automation in Process Sequence Generation*: There are two levels:
   - *Automatic*: Designer only inputs design requirements once, then the system outputs various feasible process sequences automatically.
   - *Semi-Automatic*: Designer identifies a suitable process sequence in an interactive manner by guiding the selection process.
3. *Coupling of Process and Material*: Whether the coupling of process and material is considered during the selection process.
4. *Coupling of Process and shape*: Whether the coupling of process and shape is considered during the selection process.
5. *Integration with External Cost Estimation System*: Whether a external cost estimation system is used by the system.

Table 5 shows the comparison of the four systems described in Section 2 with our system. As shown in this table our system compares favorably with all the systems on the defined criteria. It has two main novel features not found in others systems: (1) it can automatically generate process sequences for various shape modification features; and (2) it is fully integrated with an external cost evaluation system.

Table 5: Comparation of Various Material Process Selection Systems

Metrics		MAS [Smith 1999]	DA [Kunchithapatham 1996]	CPP [Feng and Zhang 1999]	CES [Ashby and Easwi 1999]	WiseProM
System	Web-based or not	Yes	No	No	No	Yes
	Number of materials	16	42	Not available	3000	52
	Number of processes	22	17	Not available	125	31
	Customization	No	No	No	Yes	Yes
Input	How input is defined	Single point	"High", "Medium", "Low"	Single point	Range	Range
Output	Single processes/Process sequences	Process sequences	Single processes	Single processes	Process Sequences	Process Sequences
	Cost report	Yes	No	No	No	Yes
	Ranking	Yes	No	No	Yes	Yes
Selection Algorithm	Algorithm	Database search	Database search	Database search	Database search	Branch and Bound and Database Search
	Amount of Automation in Process Sequence Generation	Semi-automatic	Not Available	Not Available	Not Available	**Automatic**

	Coupling of Process and Material	Yes	Yes	Yes	Yes	Yes
	Coupling of Process and Shape	Yes	No	Yes	Yes	Yes
	Integration with External Cost Estimation System	No	No	No	No	Yes

10.2 Summary

In this paper we have described a systematic approach to material and process selection during embodiment design of mechanical components, algorithms for supporting various steps in our approach, and a system for generating process and material selection advice. We follow a three-step approach to process and material selection. We first generate combinations of materials and primary processes. Then, we find the set of non-dominated sequences for each combination found in the first step by adding secondary and tertiary processes to meet detailed form requirements and pruning dominated sequences. Finally, designers can use our cost analysis functions to compare different non-dominated sequences to select the final combination of material and process sequence. We have implemented our approach and algorithms in a prototype system called WiSeProM (Wizard for Selecting Processes and Materials). Our system has the following novel features:

1. It accounts for imprecision in design parameters in selecting material and processes.

2. It automatically generates process sequences to satisfy the form requirements when a single process cannot meet all the form requirements. Unlike previous approaches, there is no restriction on the number of processes used in a sequence. Therefore, we can solve problems that require four or more processes.

3. It is accessible using a World Wide Web browser.

4. Databases and algorithms are completely separated. Therefore, as soon as new material and/or process information is added into the database, it can be immediately used in our system.

We believe that our system will allow designers to explore a large number of material and process options during the embodiment design stage and to select the most cost-effective combination. By selecting the material and process combination during the early design stages, designers can ensure that the detailed design is compatible with all of the process constraints for the selected processes.

10.3 Current Limitations

Current system has the following limitations:

- We only have a general material and process database. Process and material instances that differ in properties from the general database are not supported.
- We have not considered those classes of processes that change material properties such as annealing and quenching.
- We only use cost estimation software SEER-DFM to do cost estimation. Due to the limitation of SEER-DFM, only limited number of processes and materials are supported to do cost estimation.
- The assumption of the system is that all processes and materials included in the database are available to designer. Designers may not have access to all the manufacturing resources included in the system. In the future, system should provide designer the functionality to specify those processes that are not available.
- The system uses very restrictive definitions of production tool lead-time and production rate parameters. In general, these parameters depend on the manufacturing facility. Improvements will be needed to handle these parameters in a better way.
- If no suitable process material combination is found, the system does not recommend how to modify design requirements.
- Current cost estimation only estimates manufacturing costs. Life cycle costs may play a major role in the decision and they should be considered in future extension.
- Current system handles one component at a time. One possible extension will be to extend the system to work with assemblies.

Acknowledgments. The authors gratefully acknowledge the support provided by NIST's System Integration and for Manufacturing Applications (SIMA) program, which is monitored by James Fowler. Commercial product or company names in this paper are given for informational purposes only. Their use does not imply recommendation or endorsement by the National Institute of Standards and Technology or the University of Maryland.

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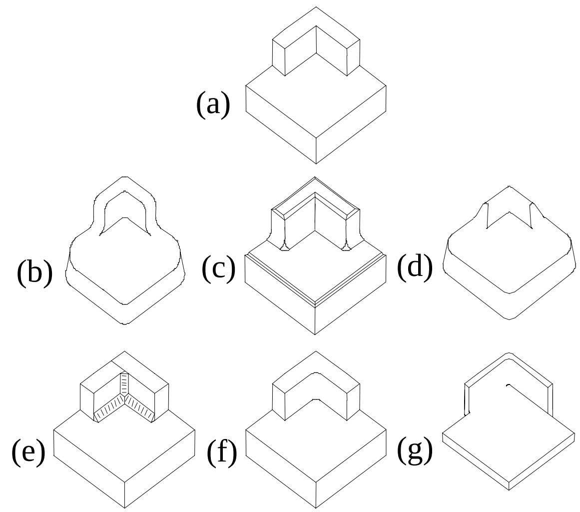

Figure 1: Various Alternative Detailed Design of a Support Bracket [Magrab 1997]

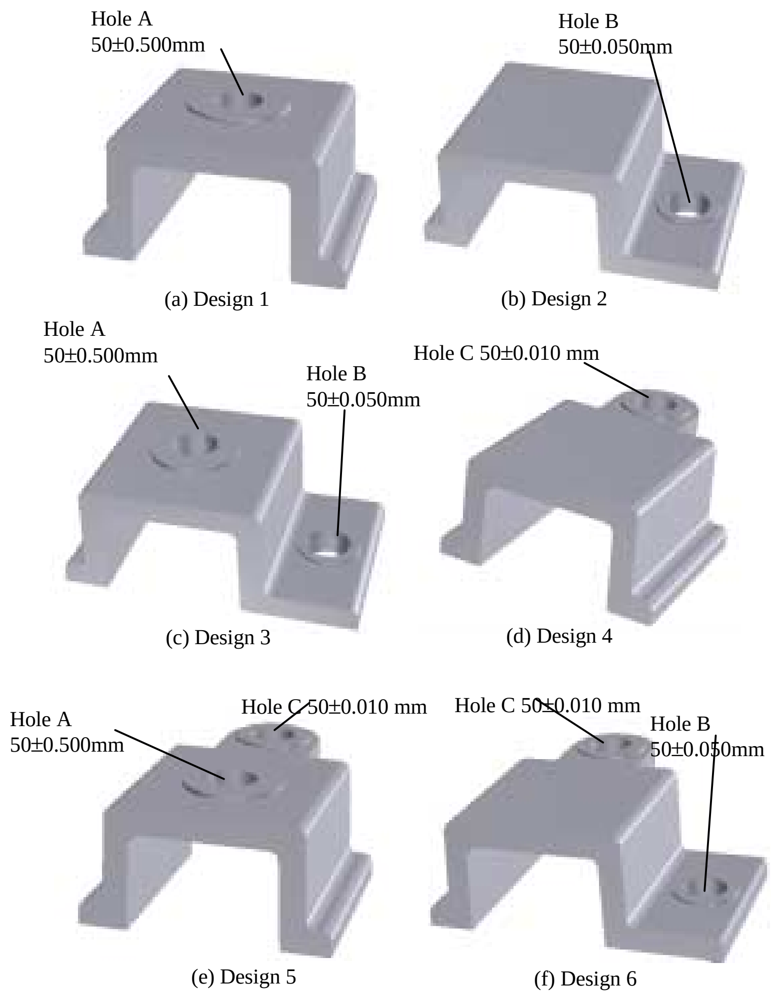

Figure 2: Examples that illustrate how presence of a feature affects the process selected for another feature

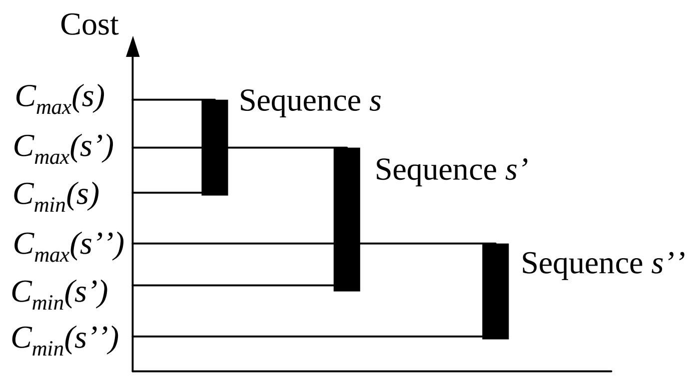

Figure 3: Dominating and Dominated Sequences

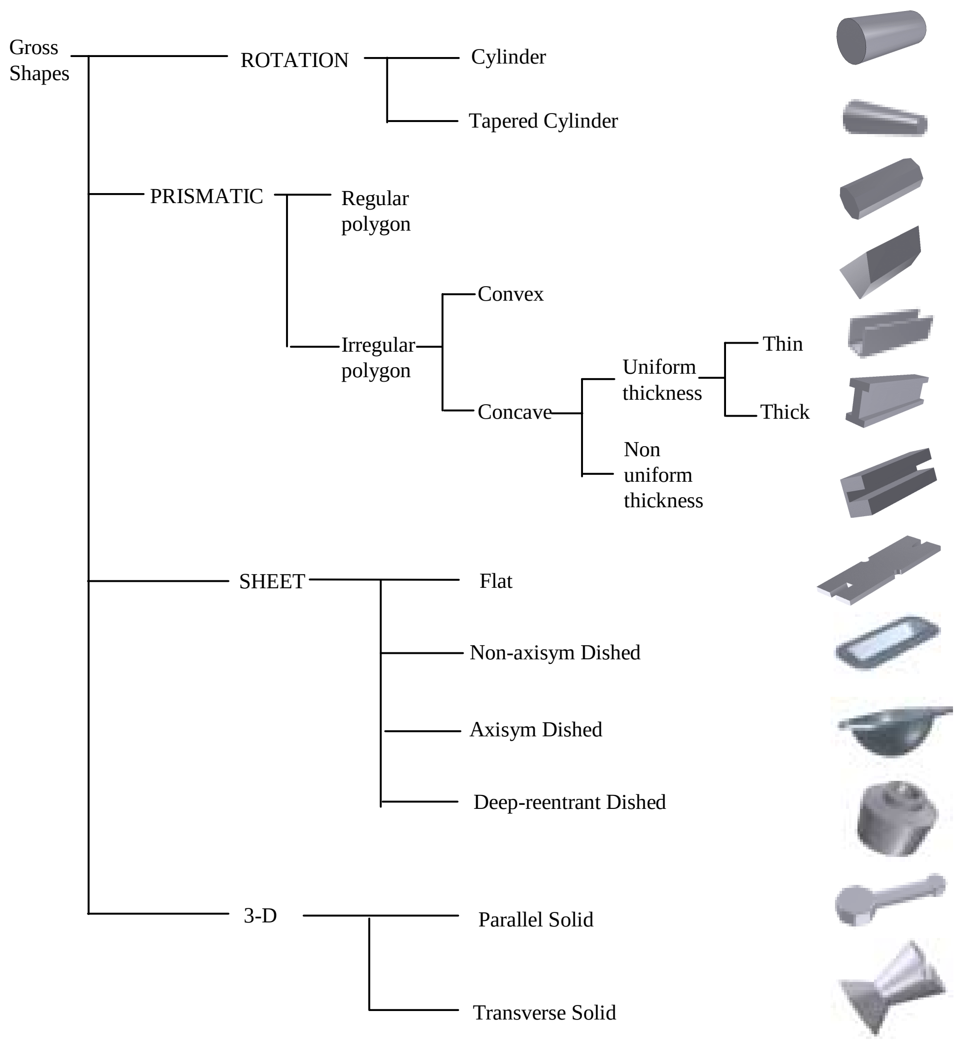

Figure 4: Gross Shape Types

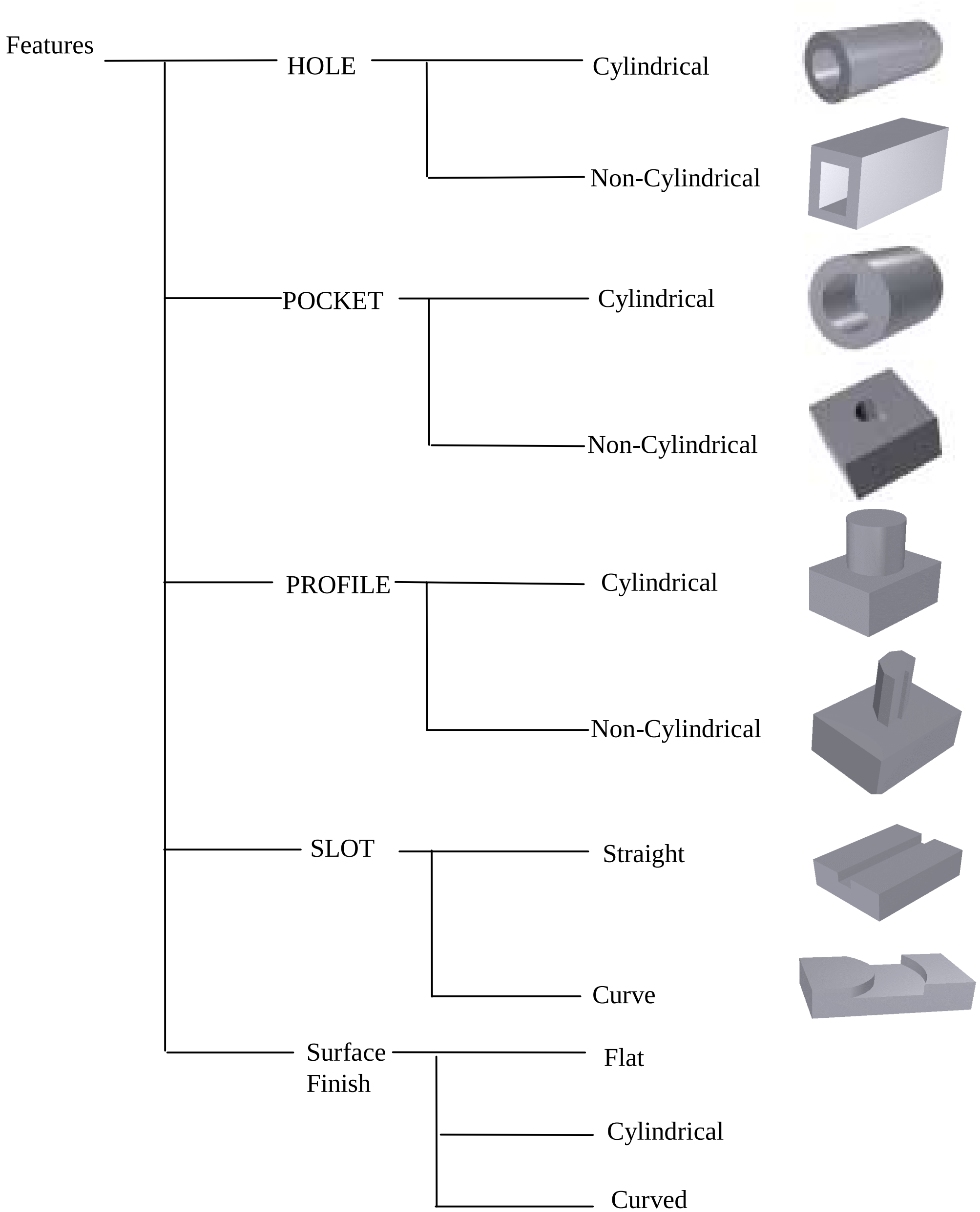

Figure 5: Shape Modification Feature Types

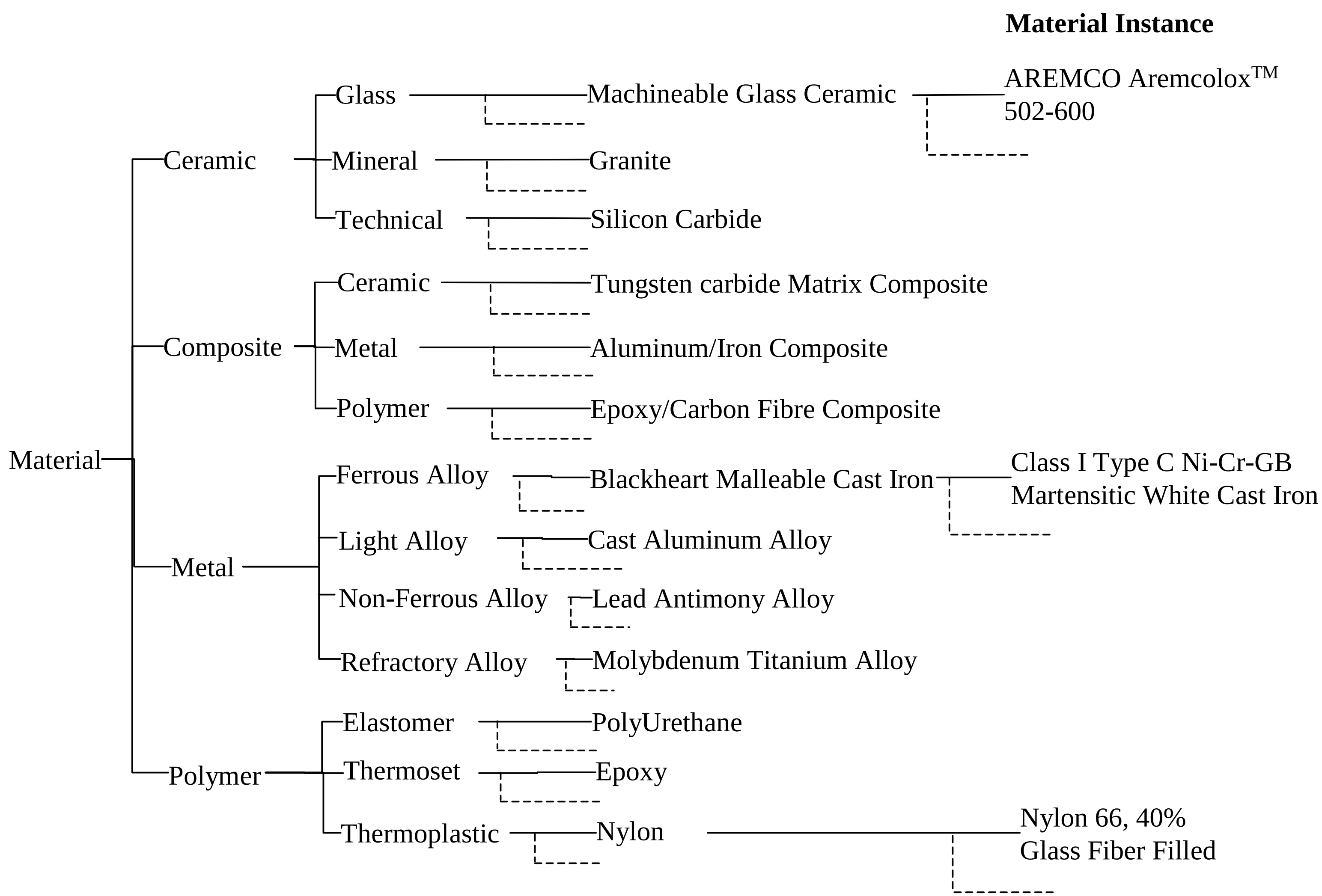

Figure 6: Material Classification

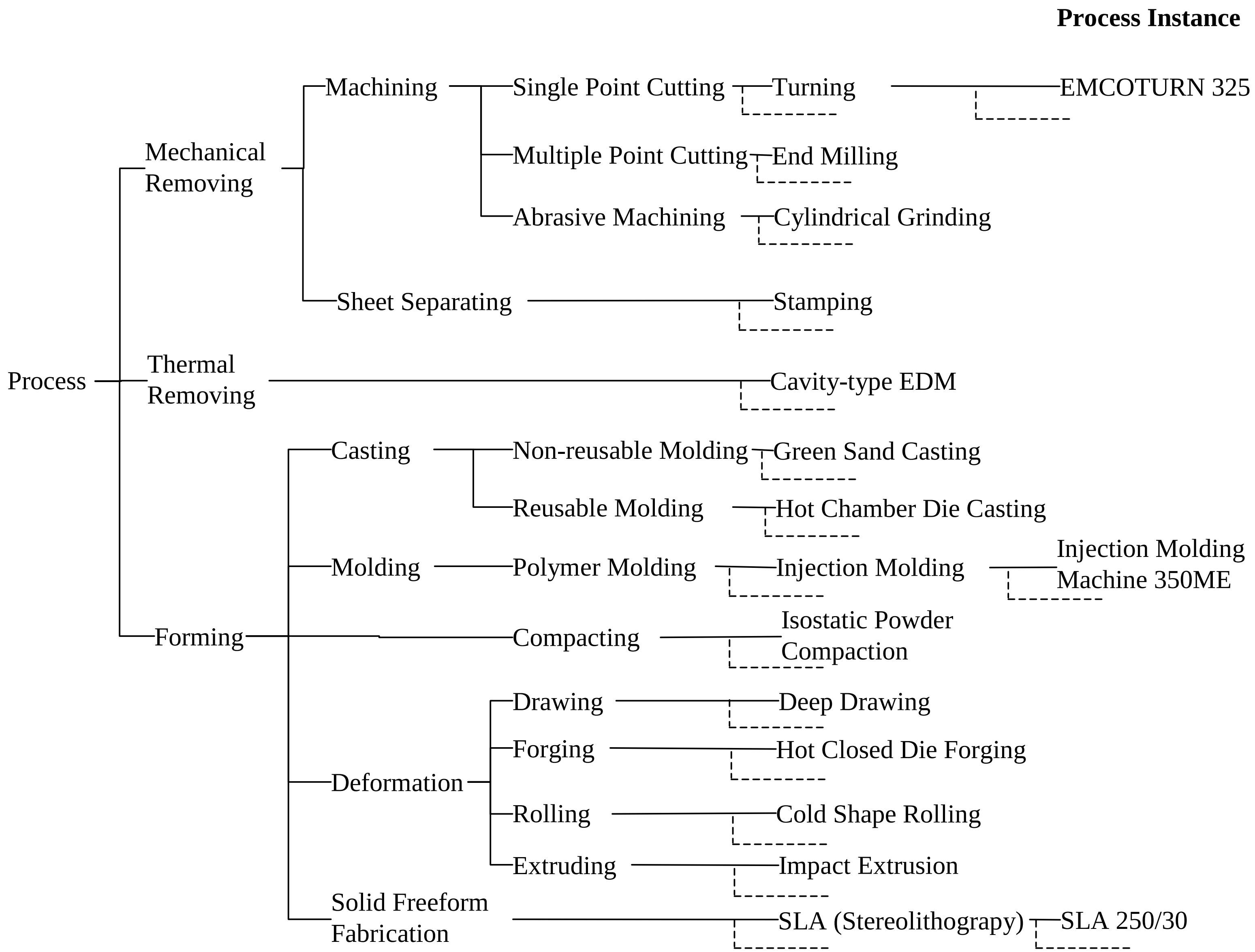

Figure 7: Process Classification

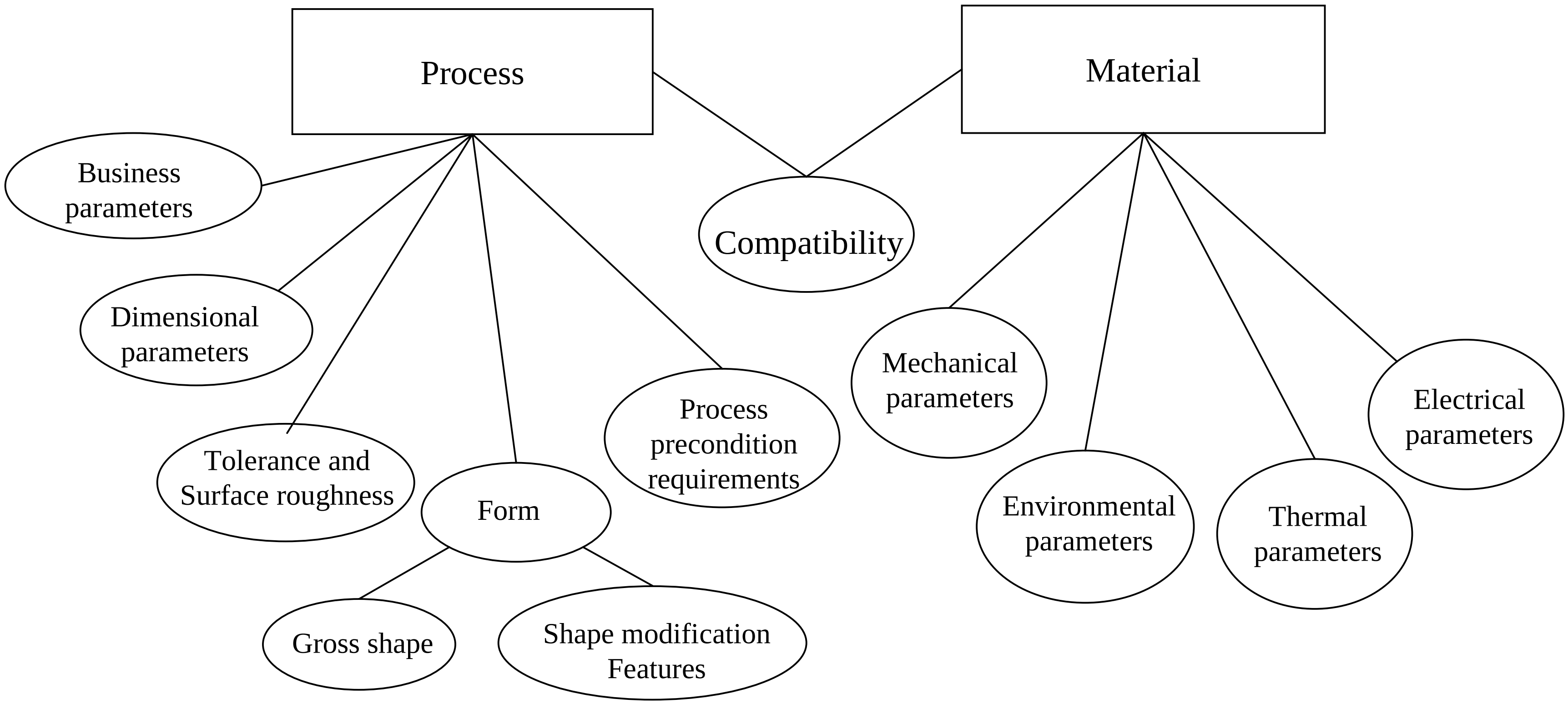

Figure 8: process material information model

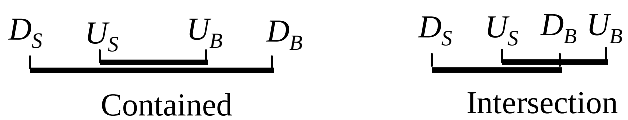

Figure 9: Two types of search

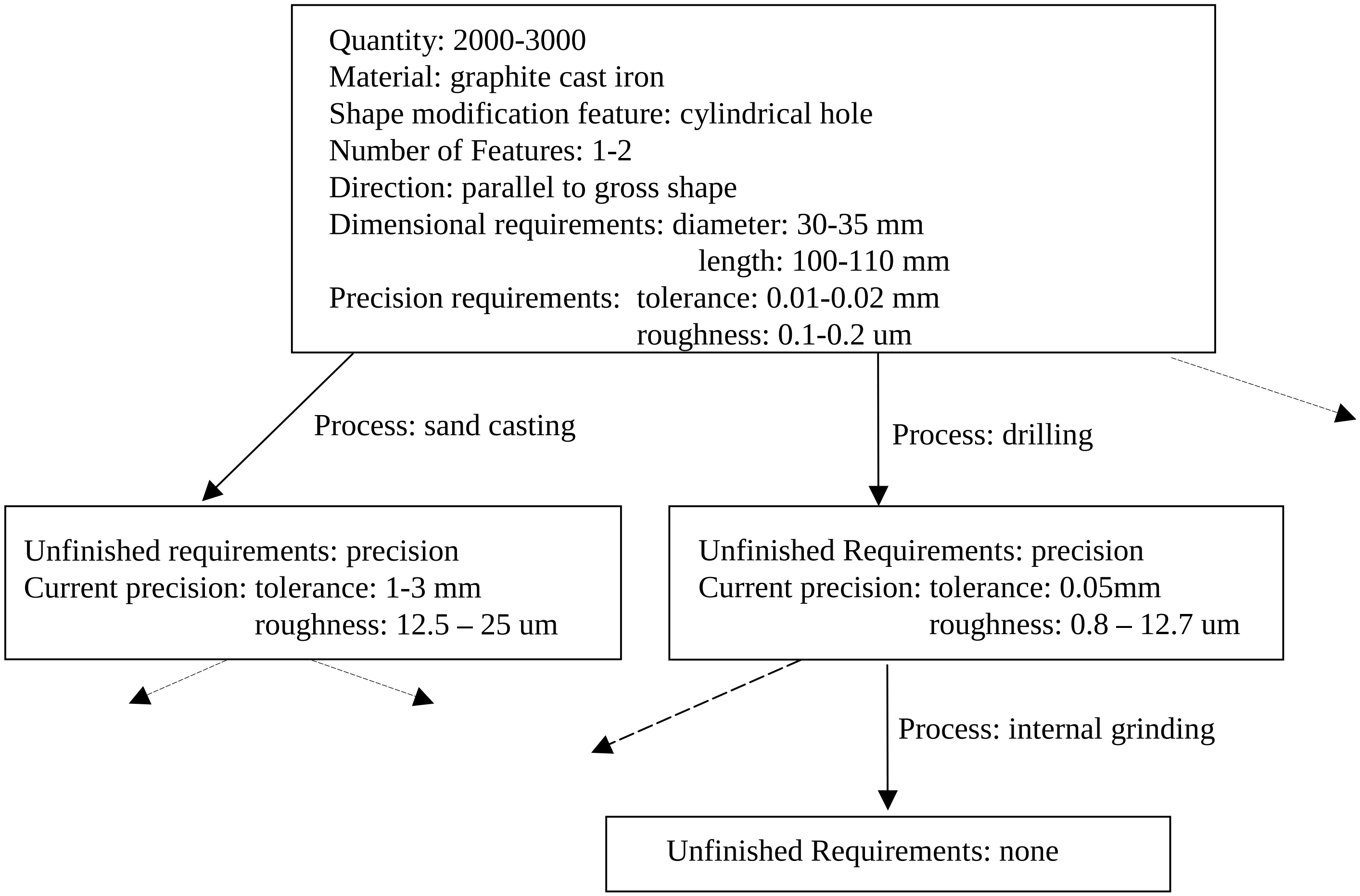

Figure 10: Example of a Process Option Tree for a Shape Modification Feature

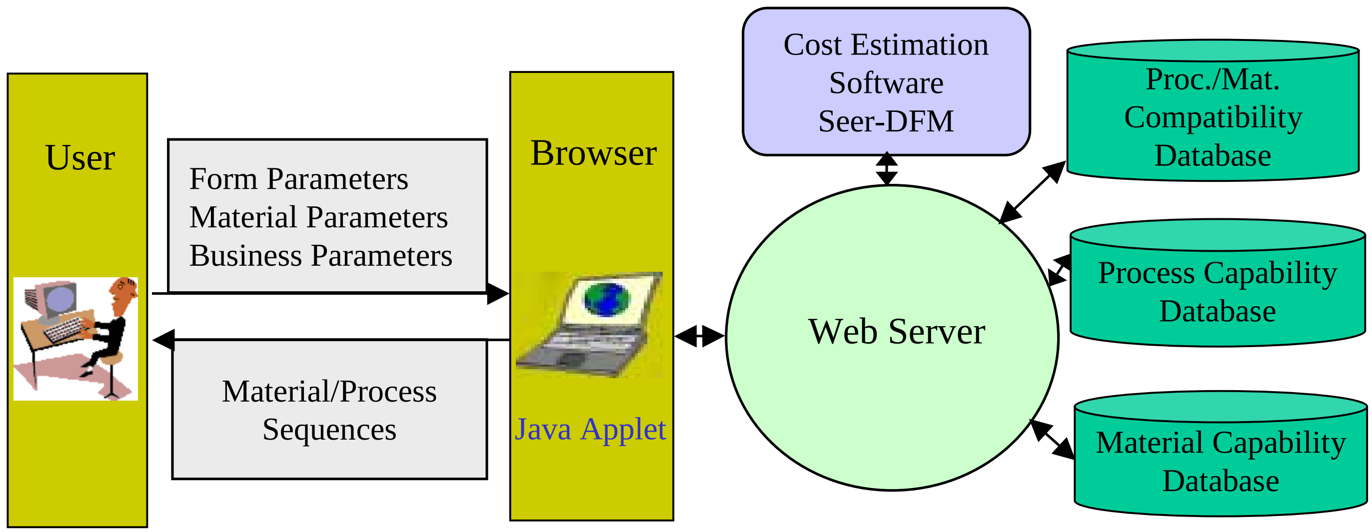

Figure 11: System Architecture

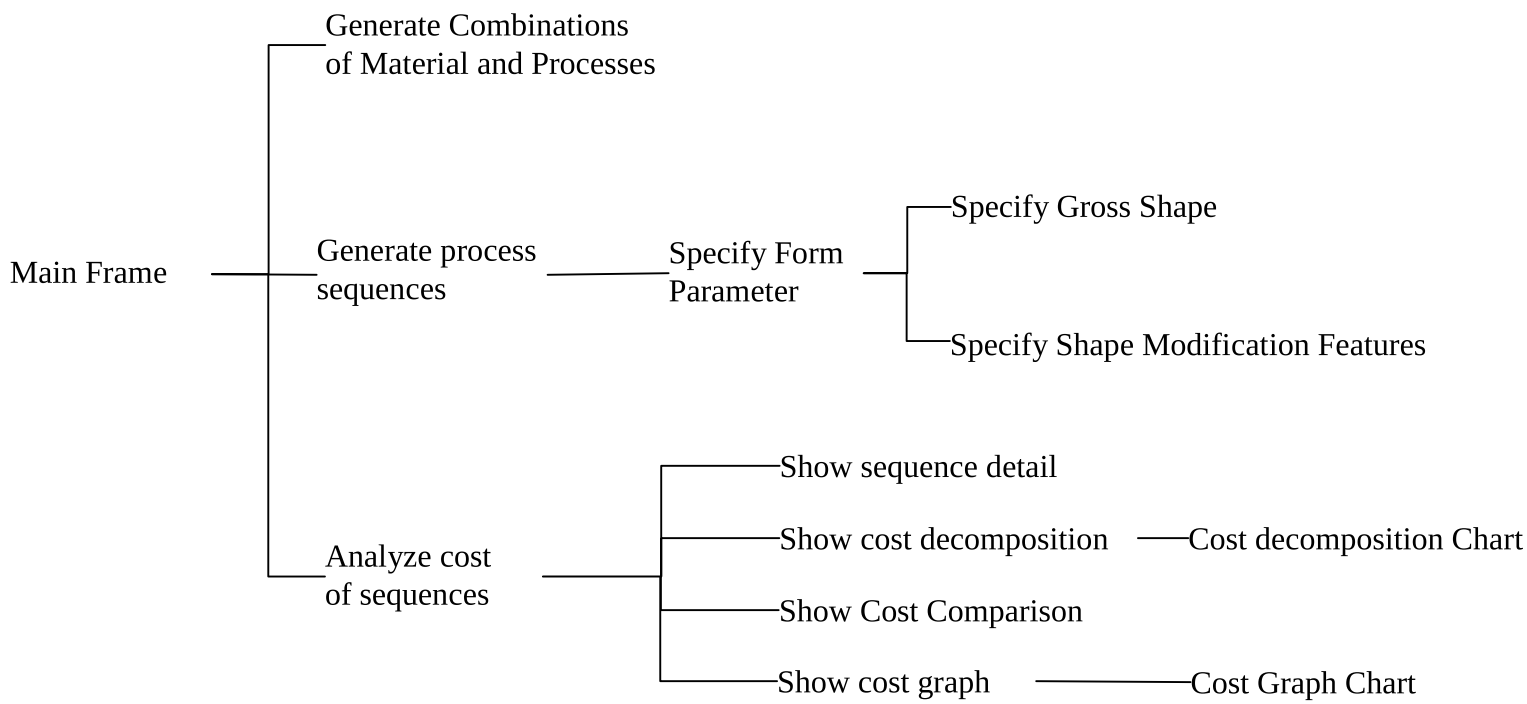

Figure 12: Relationship among Different Windows

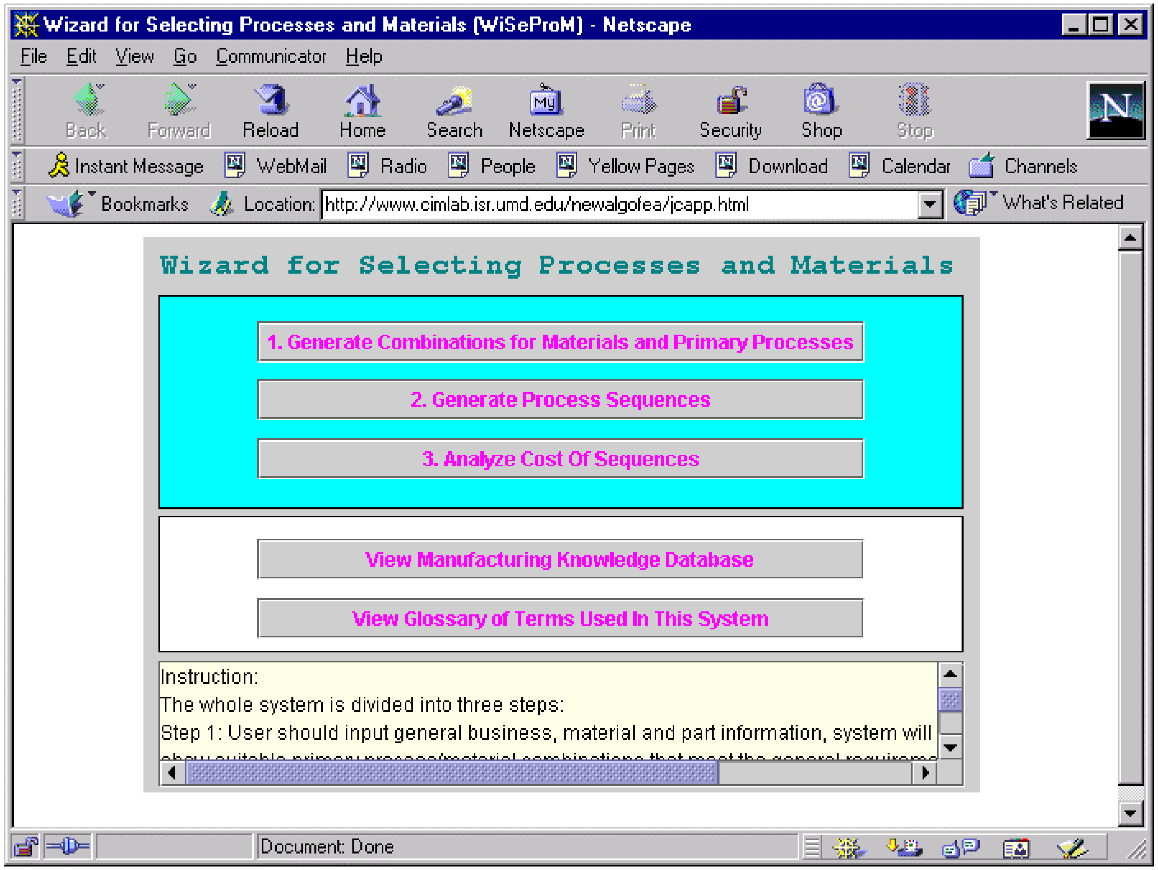

Figure 13: Main Frame

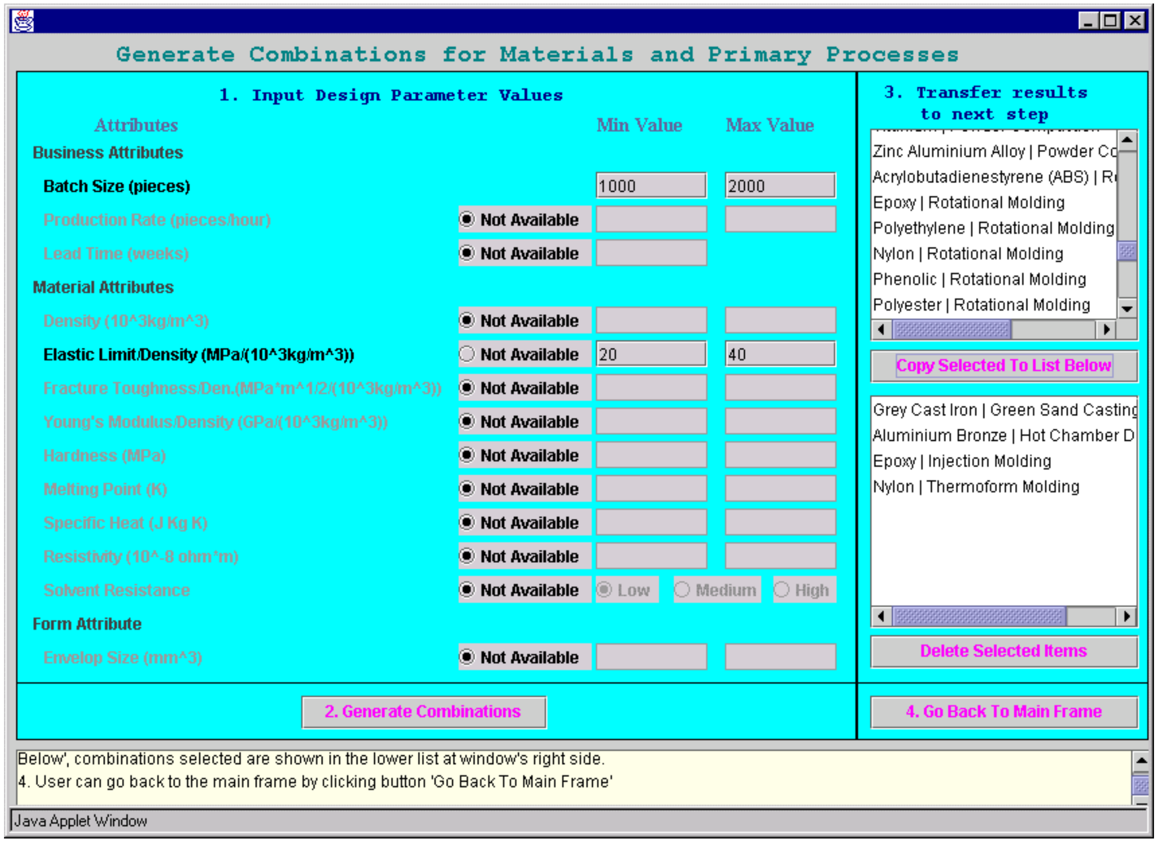

Figure 14: Window for Generating Combinations for Materials and Primary Processes

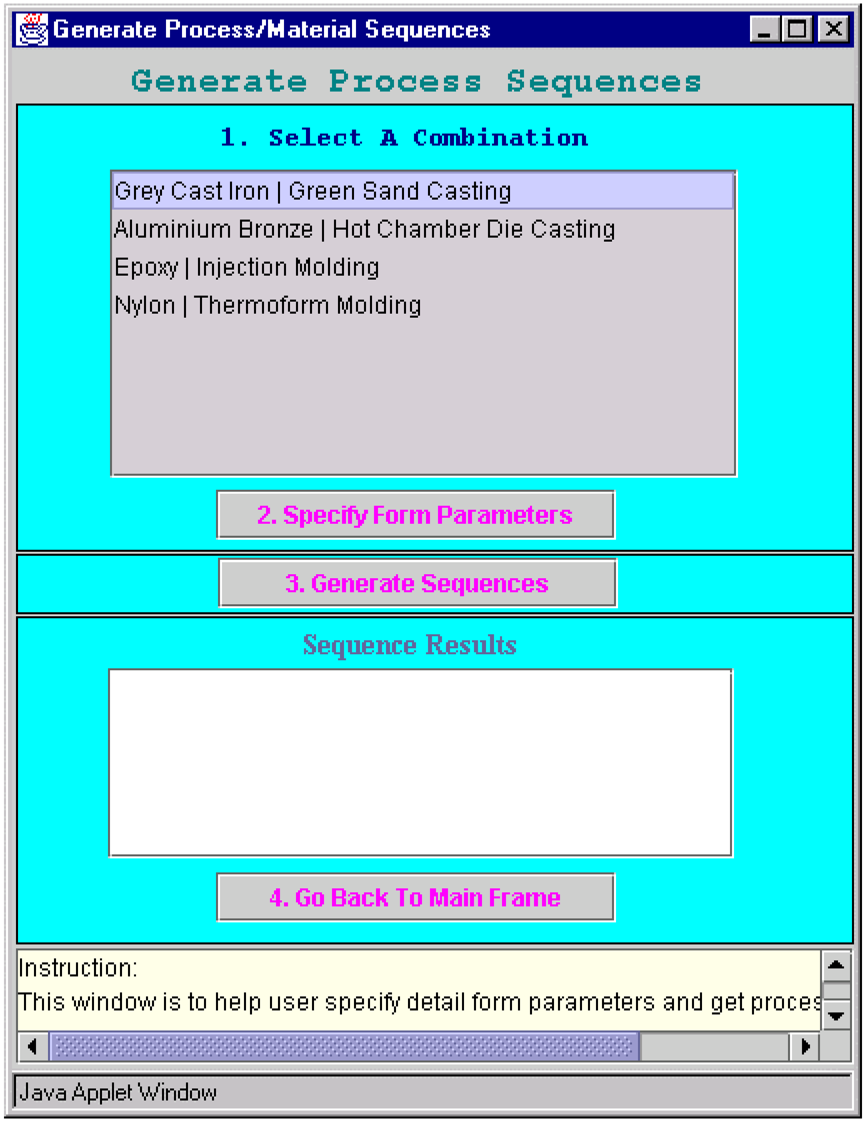

Figure 15: Window for Generating Process Sequences

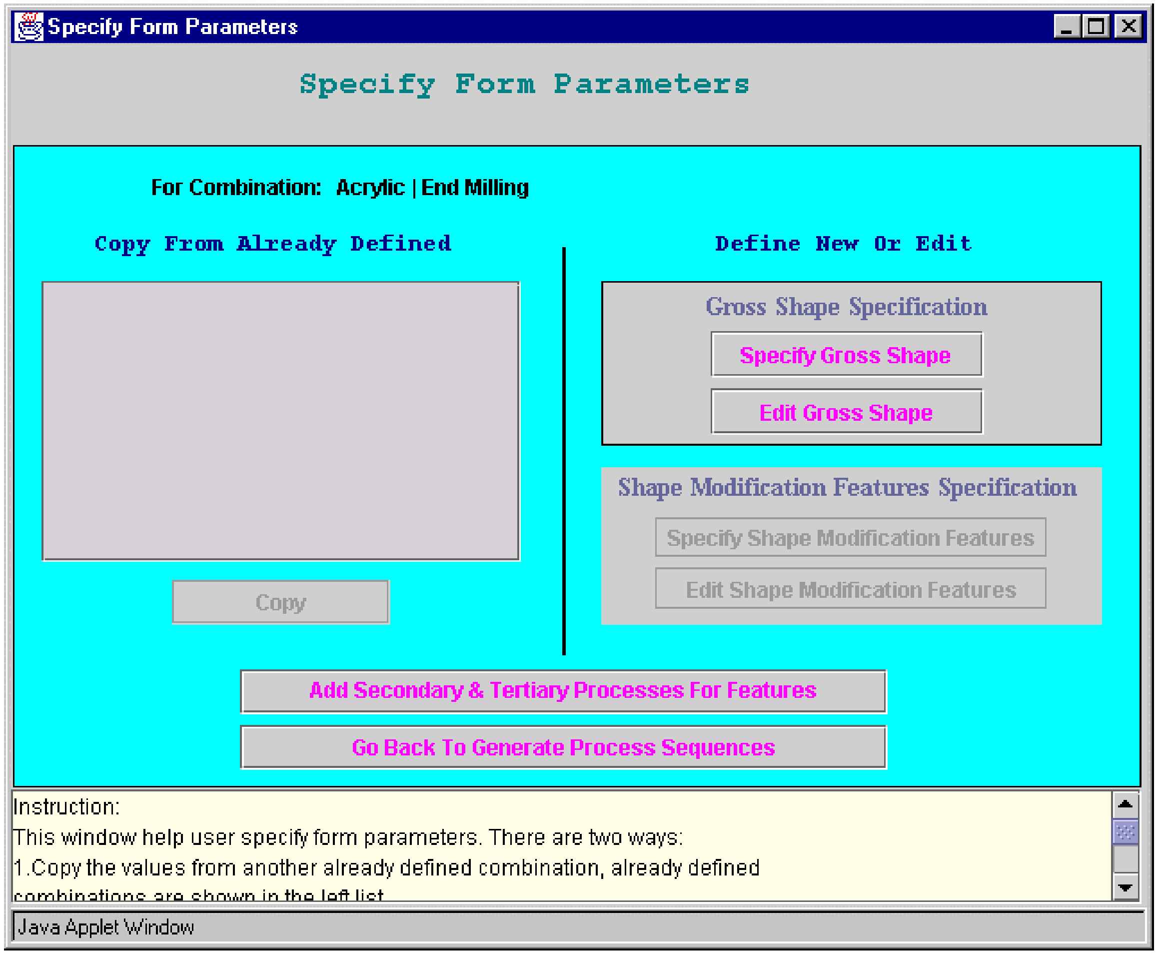

Figure 16: Window for Specifying Form Parameters

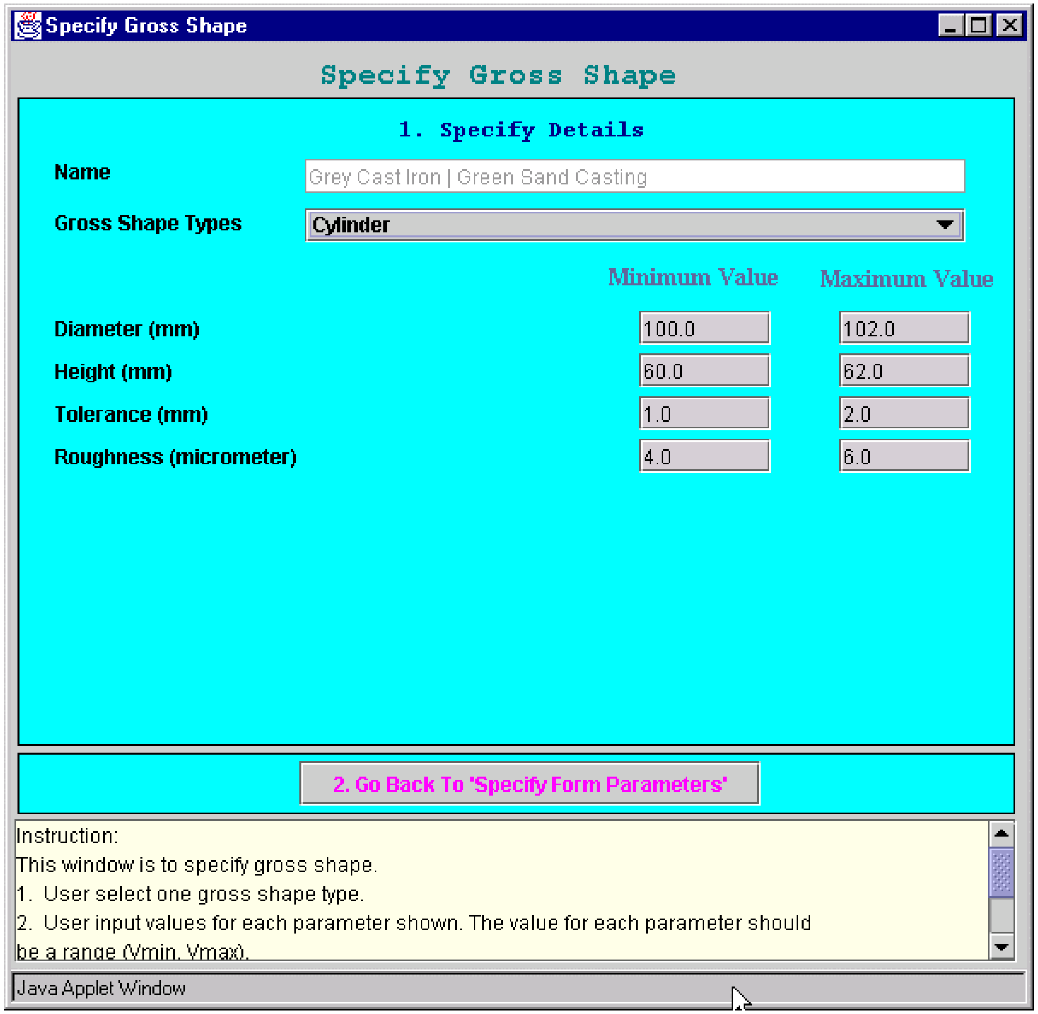

Figure 17: Window for Specifying Gross Shape

Figure 18: Window for Specifying Shape Modification Features

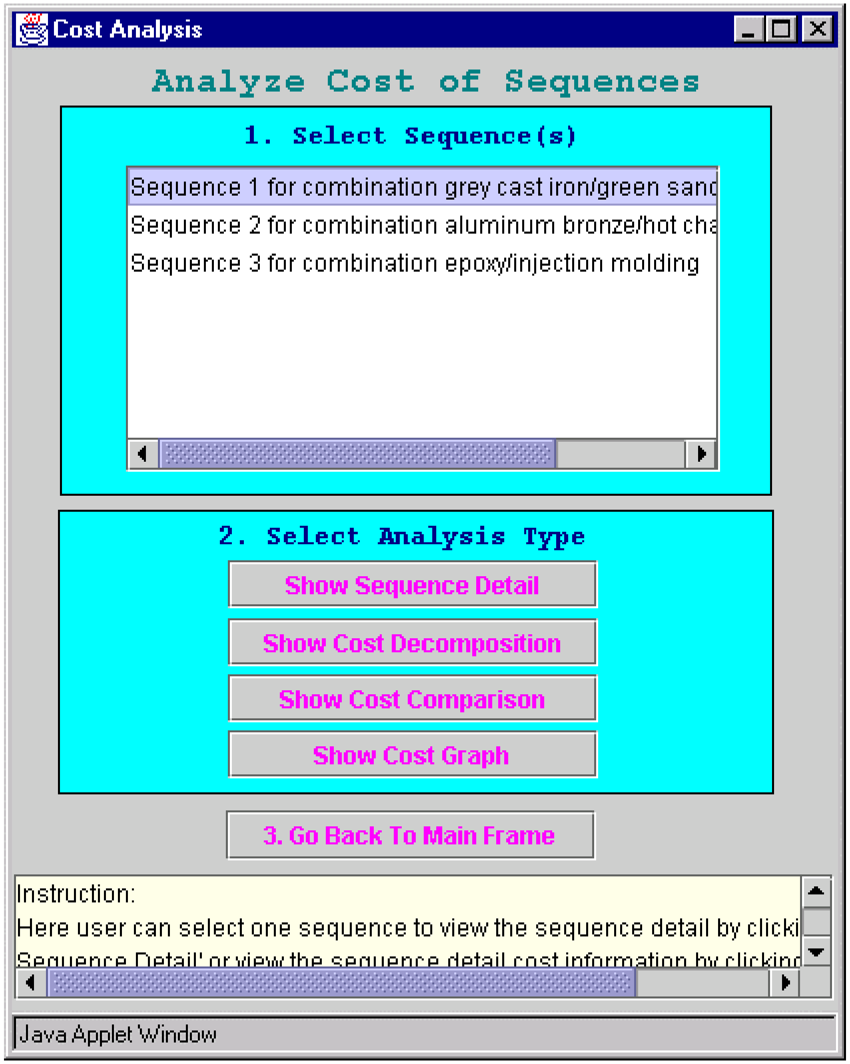

Figure 19: Window for Analyzing Cost of Sequences

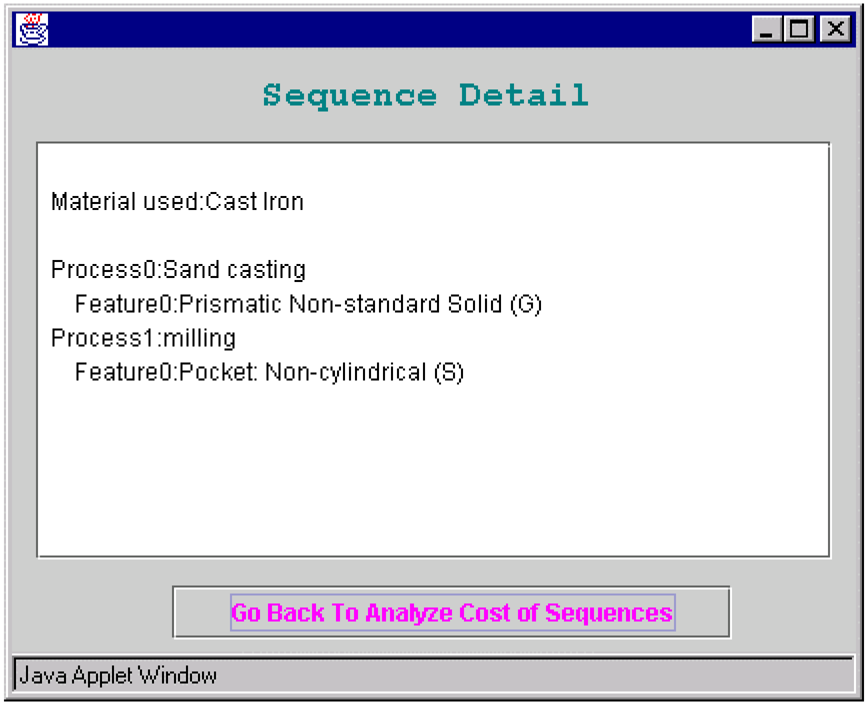

Figure 20: Window for Sequence Detail

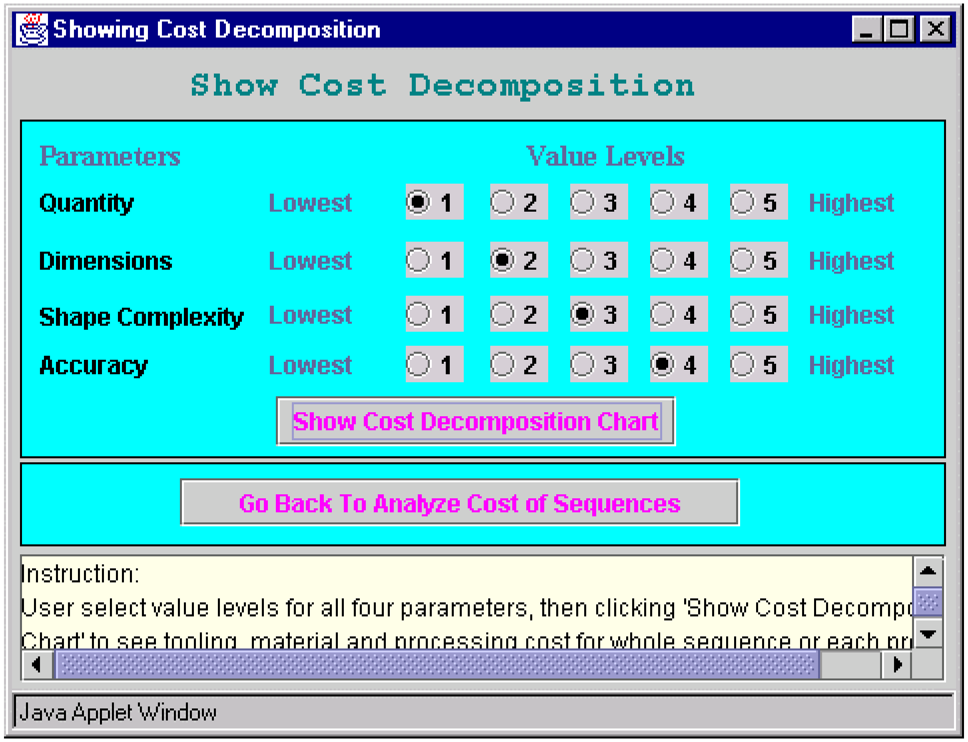

Figure 21: Window for Showing Cost Decomposition

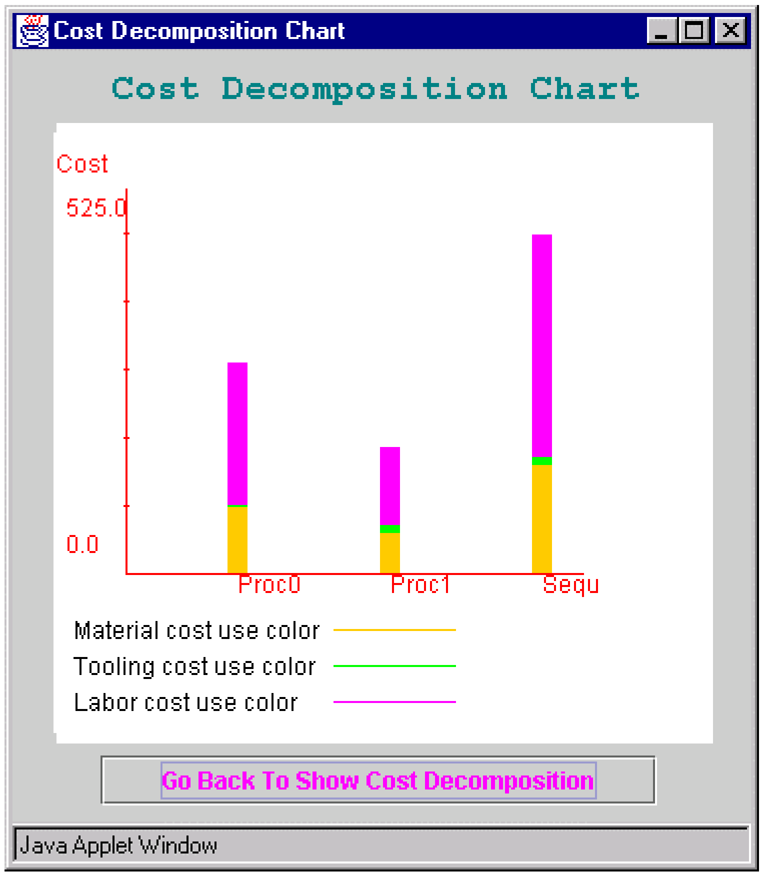

Figure 22: Window for Cost Decomposition Chart

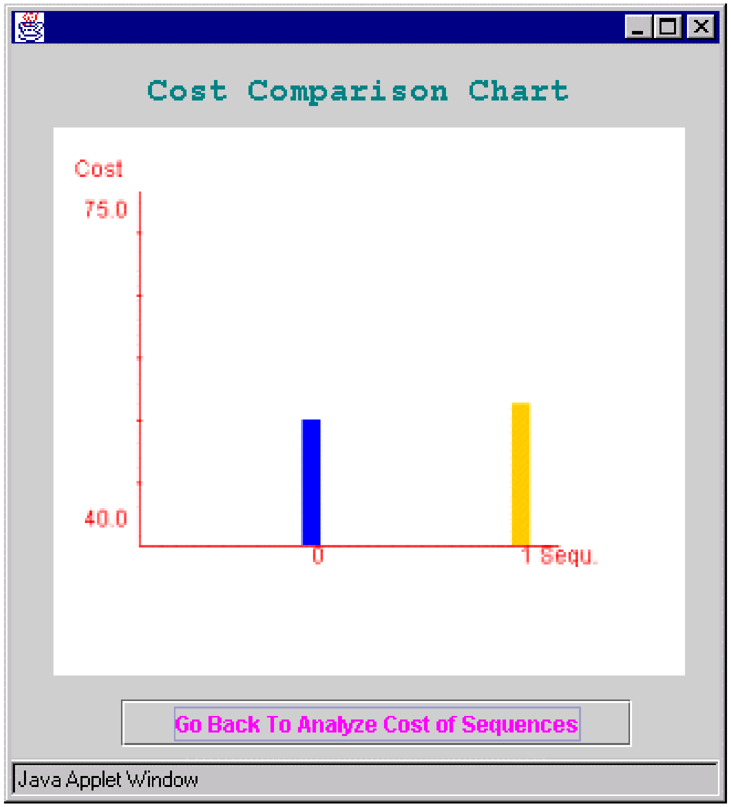

Figure 23: Window for Cost Comparison Chart

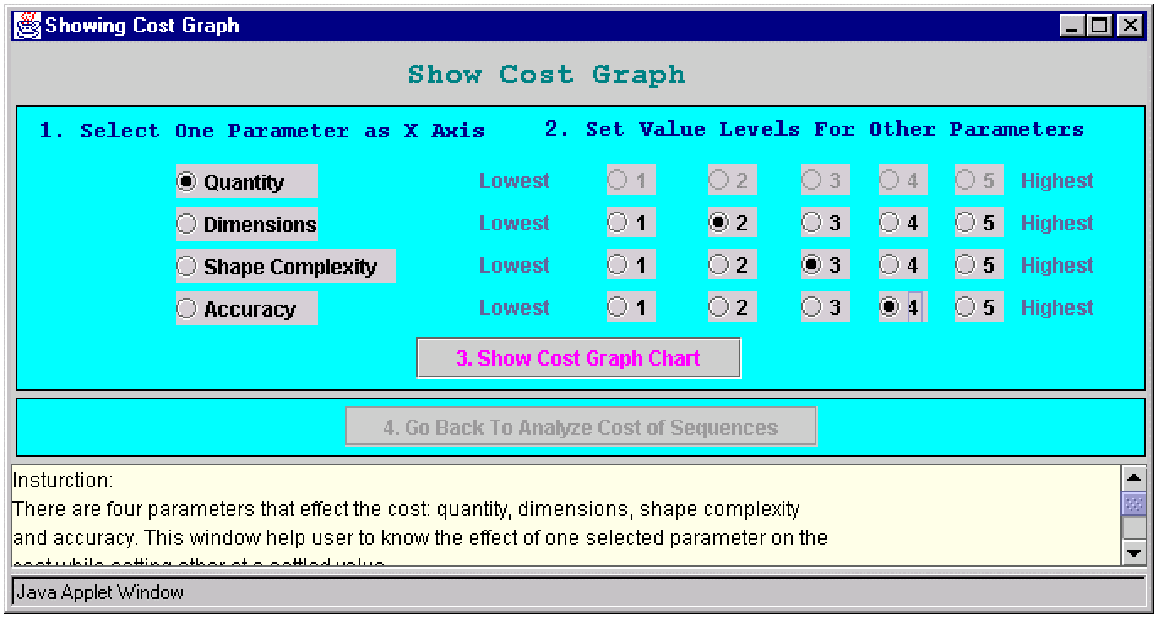

Figure 24: Window for Showing Cost Graph

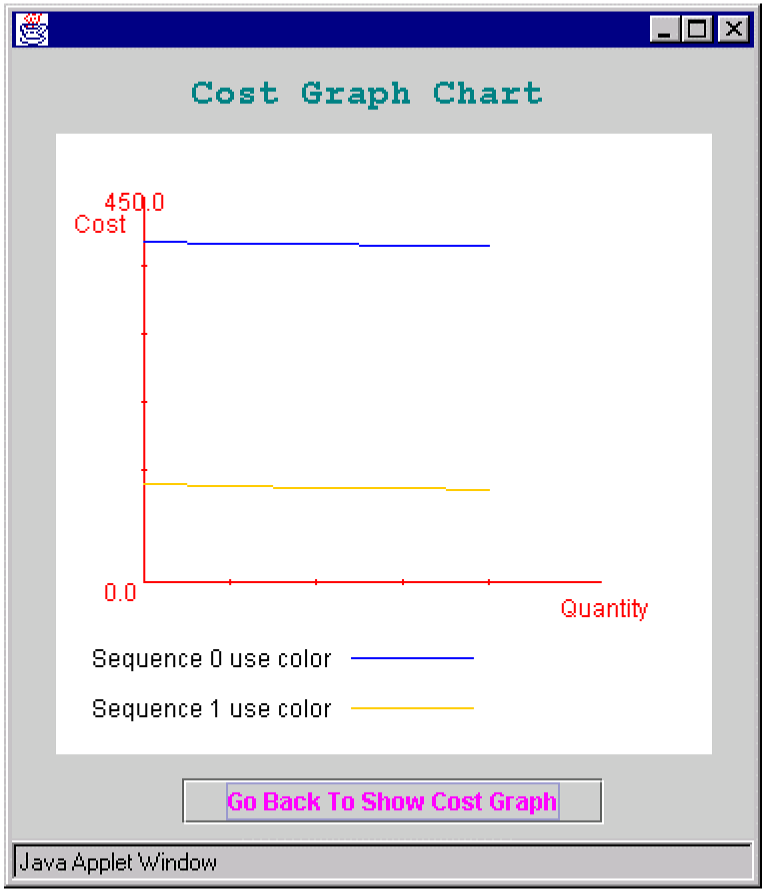

Figure 25: Window for Cost Graph Chart

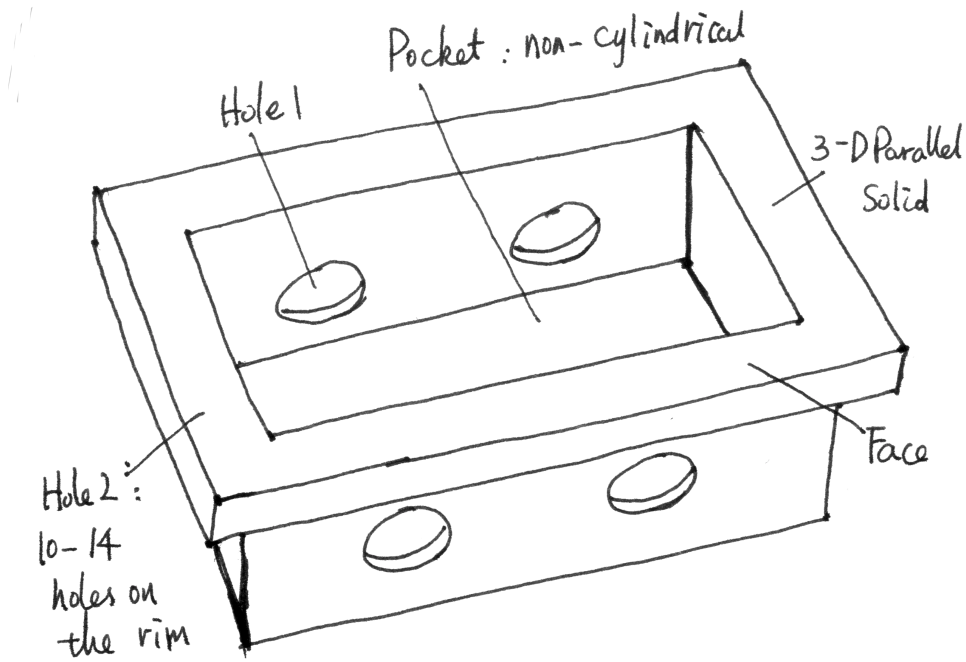

Figure 26: A rough sketch of housing

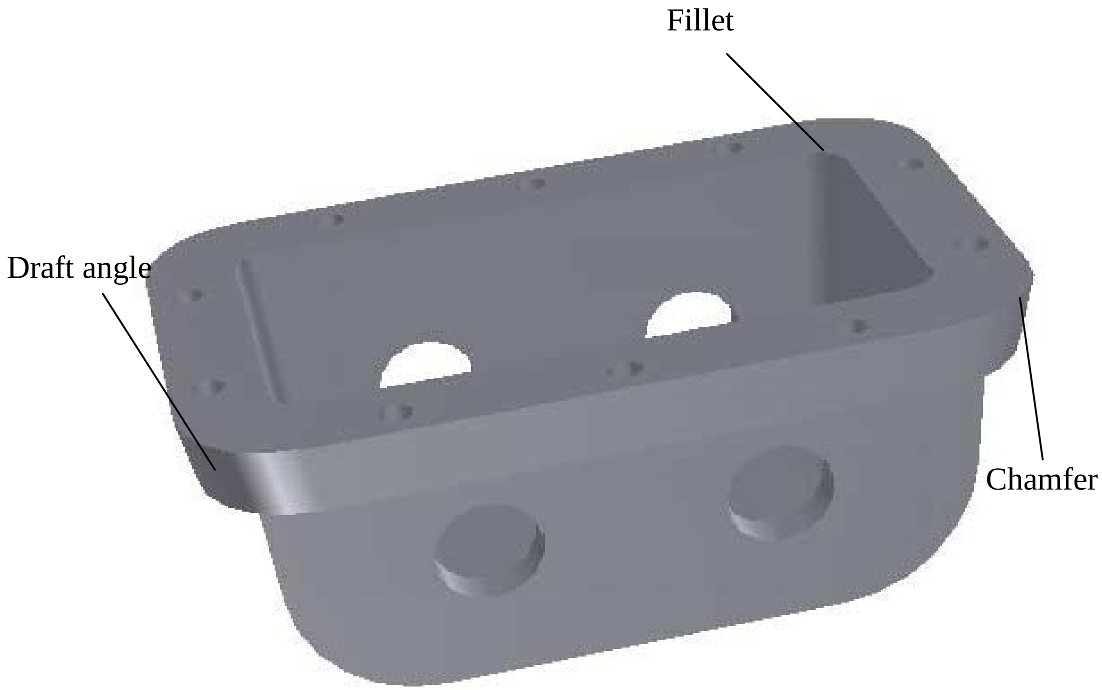

Figure 27: Process dependent design of housing

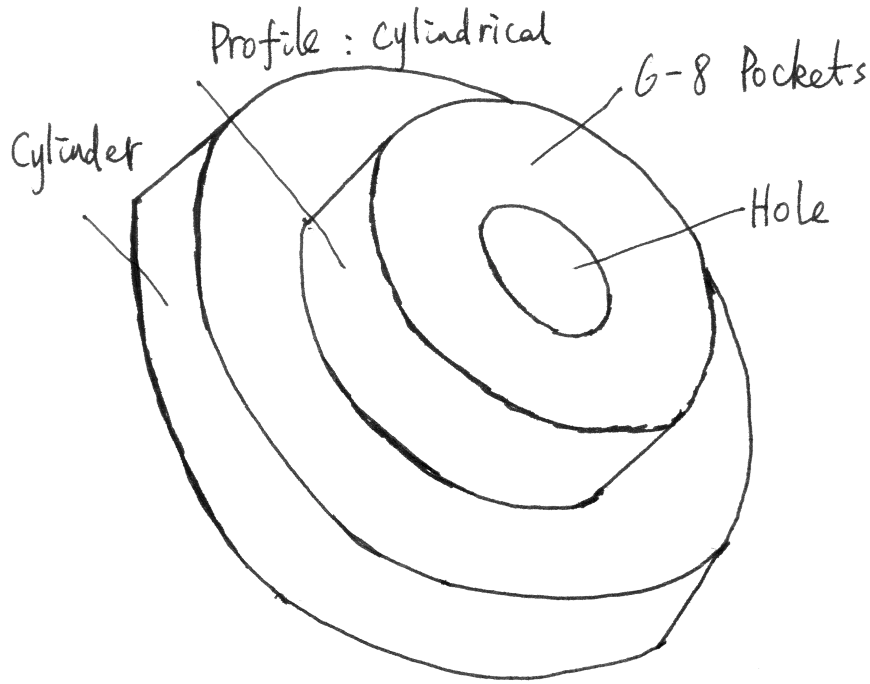

Figure 28: A rough sketch of wheel

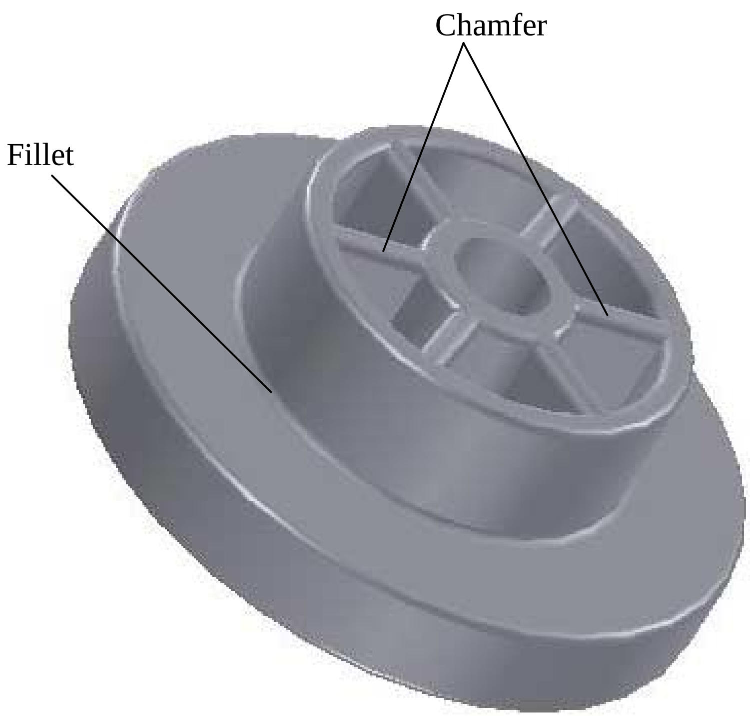

Figure 29: Process dependent design of wheel