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A WEB-BASED PROCESS/MATERIAL ADVISORY SYSTEM

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ABSTRACT

This paper describes a web-based process/material advisory system that can be used during conceptual design. Given a set of design requirements for a part during conceptual design stage, our system produces process sequences that can meet the design requirements. Quite often during conceptual design stage, design requirements are not precisely defined. Therefore, we allow users to describe design requirements in terms of parameter ranges. Parameter ranges are used to capture uncertainties in design requirements. Our system accounts for uncertainties in design requirements in generating and evaluating process/material combinations. Our system uses a two step algorithm. During the first step, we generate a material/process option tree. This tree represents various process/material options that can be used to meet the given set of design requirements. During the second step, we evaluate various alternative process/material options using a depth first branch and bound algorithm to identify and recommend the least expensive process/material combination to the designer. Our system can be accessed on the World Wide Web using a standard browser. Our system allows designs to consider a wide variety of process/material options during the conceptual design stage and allows them to find the most cost-effective combination. By selecting the process/material combination during the early design stages, designers can ensure that the detailed design is compatible with all of the process constraints for the selected process.

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 many 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 [19], this base can take many embodiments. For example, Figure 1(a) shows the desired functional design. Figures 1 (b), (c), (d), (e), (f), and (g) show cost-effective design for sand casting, powder metallurgy, forging, welding, milling, and bending respectively. This example illustrates that the final form of a component should be finalized after selecting the most appropriate process/material combination.

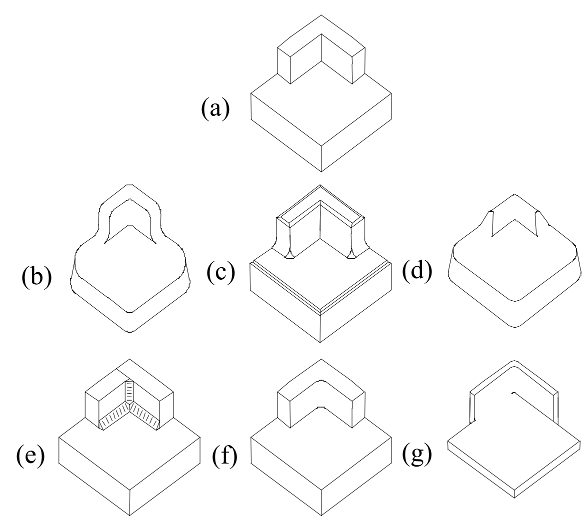

Figure 1: Various Alternative Detailed Design of a Support Bracket

Currently, process planning starts after the detailed design has been completed. This approach makes it difficult to bring manufacturing perspective during conceptual design stages. Bringing manufacturing perspective during early design stage will help in creating detailed designs whose features will be fully compatible with the manufacturing process and therefore economical to produce.

We have developed a systematic approach to selecting process/material combinations during conceptual design stage. Given a set of design requirements for a part, our system produces process/material recommendations that can meet the design requirements. Our system uses a two step algorithm. During the first step, we generate a process/material option tree. This tree represents various process/material options that can be used to meet the given set of design requirements. We store process and material parameters in the following three databases: process database, material database, and process/material compatibility database. These databases are used to generate the process/material option tree. During the second step, we evaluate various possible process sequences using a depth first branch and bound algorithm and recommend the least expensive process/material combination to the designer. Our system can be accessed on the World Wide Web using a standard browser.

2. LITERATURE SURVEY

In Section 2.1, we first present a broad overview of literature in this area. In Section 2.2, we compare four existing systems that have functionality similar to our system.

2.1 Overview

Manufacturability Analysis: A wide variety of computational methods have emerged to provide software-aids for performing manufacturability analysis [13]. The majority of manufacturability analysis research is focussed towards creating software tools applicable during design analysis. Such systems vary significantly by approach, scope, and level of sophistication. At one end of the spectrum are software tools for providing estimates of the approximate manufacturing cost. At the other end are sophisticated tools that perform detailed design analysis and offer redesign suggestions. For analyzing the manufacturability of a design, the existing approaches can be roughly classified into the following two categories. In *direct* approaches [15, 16, 22, 24], 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 [7, 8, 12, 26] the first step is to generate a manufacturing plan, and modify various portions of the plan in order to reduce its cost. This approach is useful in domains where manufacturing operations interact with each other in complex ways. Descriptions of representative manufacturability analysis systems can be found in [2, 3, 8, 9, 11, 14, 15, 16, 20, 23, 24, 27, 28]. Analysis based systems are a step in the right direction and leading to cost savings.

Process/Material Selection during Conceptual Design: Recently research is being reported in the area of extending manufacturability considerations into early design stages [4, 10, 20, 21]. Below we summarize four systems that help designers select material/process during conceptual design stage.

- Ashby et al [1] have developed a commercial software called Cambridge Engineering Selector (CES). It includes about 3,000 materials and 125 processes in its database. User can input desired ranges of parameters by graphical or textual interface. CES system uses database search techniques to locate the suitable combination of processes and materials. Each process in CES database has a parameter that states whether it is a primary, secondary or tertiary process. However, the user needs to manually select the process sequence.
- Kunchithapatham [18] has developed a Material/Process Advisory System. This system includes 42 materials and 17 processes in its database. It has three databases: Materials Database, Process Database and Material/Process Compatibility Database. Rather than storing the actual values of various process/material parameters, in this system, process/material data is stored using three levels: high, medium and low. This system does not incorporate specifics of shape in material/process selection.
- Smith [25] 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. User can only input one number for each design parameter. This system incorporates shape in the process selection. It provides process sequence, but the user 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 cost model to rank results.
- Feng et al [6] have developed a Conceptual Process Planning program 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.

2.2 Comparing Different Process/Material Selection Systems

Figure 2 shows the basic structure of a process/material advisory system. The user inputs design parameters and the system chooses suitable materials and processes from a process/material database by using a selection algorithm, and then outputs the result.

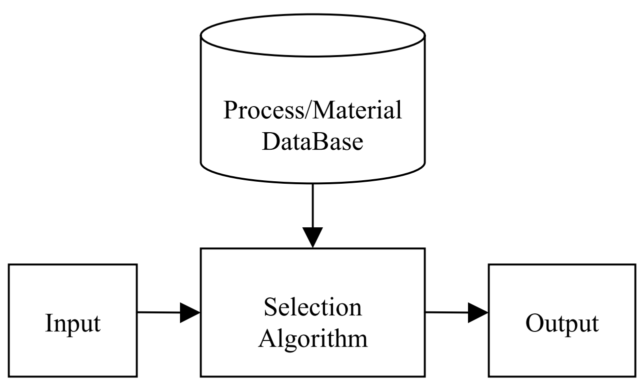

Figure 2: Process/Material Advisory System Architecture

To compare different systems, we have defined the following metrics:

System Level Characteristics:

1. *Web-Compatibility*: Whether the program is designed for using on Internet.
2. *Level of Automation*: There are two levels:
   - *Automatic*: User only inputs design parameters once, then the system outputs various feasible process sequences ranked by their relative costs automatically.
   - *Semi-Automatic*: User identifies a suitable process sequence in an interactive manner by guiding the selection process.

Nature of Input:
1. *Types of parameters inputted*: Parameters can be divided into three groups: form, material and business.
2. *Number of parameters inputted*: Number of parameters for each type.
3. *How input is defined*: Whether the data is inputted as a single value, a range (defined by two values), or a qualitative description.

Table 1: Comparation of Four Existing Systems

Metrics		MAS2.0 [25]			MPAS [18]		
System	Web-based or not	Yes			No		
	Automation	Semi-automatic			Semi-automatic		
Input	Types of parameters inputted	Form	Material	Business	Form	Material	Business
	Number of parameters inputted	8	6	5	4	10	3
	How input is defined	Single point			"High", "Medium", "Low"		
Database	General database	Yes			Yes		
	Special database	No			No		
	Number of materials	16			42		
	Number of processes	22			17		
	Customization	No			No		
	Error Checking in customization	No			No		
Output	Single processes/Process sequences	Process sequences			Single processes		
	Cost report	Yes			No		
	Ranking	Yes			Yes		
	Suggestion	No			No		
Selection Algorithm	AI based/database search	Database search			Database search		
	Coupling of Process and Material	Yes			Yes		
	Coupling of Material and Shape	No			No		
	Coupling of Process and Shape	Yes			No		
	Cost model	Yes			No		
Metrics		CPP [6]			CES [1]		
System	Web-based or not	No			No		
	Automation	Semi-automatic			Semi-automatic		
Input	Types of parameters inputted	Form	Material	Business	Form	Material	Business
	Number of parameters inputted	5	0	1	10	21	5
	How input is defined	Single point			Range		
Database	General database	Yes			Yes		
	Special database	No			Yes		
	Number of materials	Not available			3000		
	Number of processes	Not available			125		
	Customization	No			Yes		
	Error Checking in customization	No			Yes		
Output	Single processes/Process sequences	Single processes			Process Sequences		
	Cost report	Yes			No		
	Ranking	No			Yes		
	Suggestion	No			No		
Selection Algorithm	AI based/database search	Database search			Database search		
	Coupling of Process and Material	Yes			Yes		
	Coupling of Material and Shape	No			Yes		
	Coupling of Process and Shape	Yes			Yes		
	Cost model	Yes			Yes		

Database:
1. *General database*: Data is defined for classes of materials/processes. For example, data is available for a material class such as low carbon steels.
2. *Specialized database*: Data is defined for instances of material/process. For example, data is available for a specific material type such as 1040 steel.
3. *Number of materials in database*: Number of materials included in database.
4. *Number of processes in database*: Number of processes included in database.
5. *Customization option*: Whether user can customize the database.
6. *Error checking in customization*: Whether errors are checked automatically in customization.

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 others.
3. *Ranking*: Whether the output can be ranked using some scheme.
4. *Redesign suggestions*: When there is no result that can meet the initial requirement, whether the system can give suggestion on how user can change the input value to have results.

Nature of Selection Algorithm:
1. *AI-Based/Database Search*: Whether the selection algorithm is AI-based or just a database search.
2. *Coupling of Process and Material*: Whether the coupling of process and material is considered during the selection process.
3. *Consideration of Shape*: Whether the shape attributes are considered during selection.
4. *Cost model*: Whether a cost model is used by the system.

Table 1 shows the comparation result.

3. OVERVIEW OF OUR APPROACH

Usually at the beginning of the conceptual design stage, designers are given functional requirements and relevant business requirements such as time-to-market, likely production volume, and total production quantity. During the conceptual design stage, designers identify critical design requirements such as envelop size, material requirements, gross shape, form features, tolerances, surface finish requirements etc. At this stage there exist sufficient information to start preliminary process planning (e.g., material and process selection). We interested in considering alternative process sequences and compatible materials that can meet these critical design requirements and selecting the process sequence that can meet these requirements with the minimum cost.

3.1 Problem Statement

We are given design requirements R_D in terms of the following:

- *Material Requirements (R_M)*: These requirements are stated in terms of required ranges of yield strength, density, hardness, corrosion resistance, magnetic properties, thermal conductivity, operating temperatures, etc.
- *Form Requirements (R_F)*: These requirements are stated in terms of envelop size, desired gross shape, likely form feature types (for example, under-cuts, overhangs, holes, and tapers), number of form features, tolerances, surface finish, etc.
- *Business Requirements (R_B)*: These requirements are stated in terms of ranges on required lead-time, production rate, and overall production quantity.

We are interested in finding a process sequence that can meet these requirements with the minimum total production cost. Total production cost C is defined as:

$$C = C_P + C_M + C_T$$

where C_P is process cost, C_M is material cost, and C_T is tooling cost.

3.2 Overview of Algorithm

The processes used to manufacture a mechanical product can be classified into the following 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 the part. *Secondary processes* are form 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.

The basic idea behind our algorithm is generation and evaluation of various alternative material/process sequences. Various sequences represent high-level process plans that comprise widely different, though sensible, material/process alternatives. We use the following two step algorithm:

- *Step 1: Construct a material/process option tree G.* This tree describes various material/process combinations that can be used to meet design requirements $R_D = (R_M, R_F, R_B)$. Various edges in G represent various processes and various nodes in G represent the list of unfinished design requirements. The root note contains all design requirements in the part. Leaf nodes (also called terminal nodes) contain no design requirements. Leaf or terminal nodes correspond to the finished part. Figure 3 shows an example of the option tree. Section 4 describes our approach for constructing option tree.
- *Step 2: Evaluate option tree G based on cost models of various manufacturing processes.* We use a depth first branch and bound algorithm to evaluate G and identify the most promising process sequence. Section 5 describes our approach for evaluating option tree.

4. CONSTRUCTING MATERIAL/PROCESS OPTION TREE

Material/Process option tree is constructed using a forward chaining algorithm. We start with all the design requirements in the root node of the tree. We examine and identify material/process combinations that can satisfy one or more design requirements in the root node. Each feasible choice for a material/process combination is added as a node in the option tree. Our algorithm proceeds in an iterative manner and keeps adding successor nodes to nodes that have not been already expanded. When the tree reaches a stage where it consists of only expanded and terminal nodes (i.e., nodes with no design requirements), the algorithm stops. A path from the root node to the terminal node presents a sequence of operations that can meet the design requirements. Procedure for generating option tree is given below.

1. Let G = empty set.
2. Insert (R_M, R_F, R_B) into *G*.
3. Find the set of node *N* in *G* that (1) have no successors, (2) are not terminal nodes, and (3) have not been already expanded.
4. If *N* is empty then stop.
5. Otherwise, for every *n* in *N*, do the following:
   a. Identify the set of process/material combination *P* that are:
      I. compatible with the predecessors of *n;*
      II. can meet one or more unfinished requirements *R* in *n*.
   b. For every *p* in *P*, do the following:
      I. Add a node *n'* as a successor of n.
      II. Let *R'* be the design requirement met by *p*.
      III. For *n'* set the unfinished requirements to be *R – R'*.
   c. Mark *n* as expanded.

6. Go to Step 3.

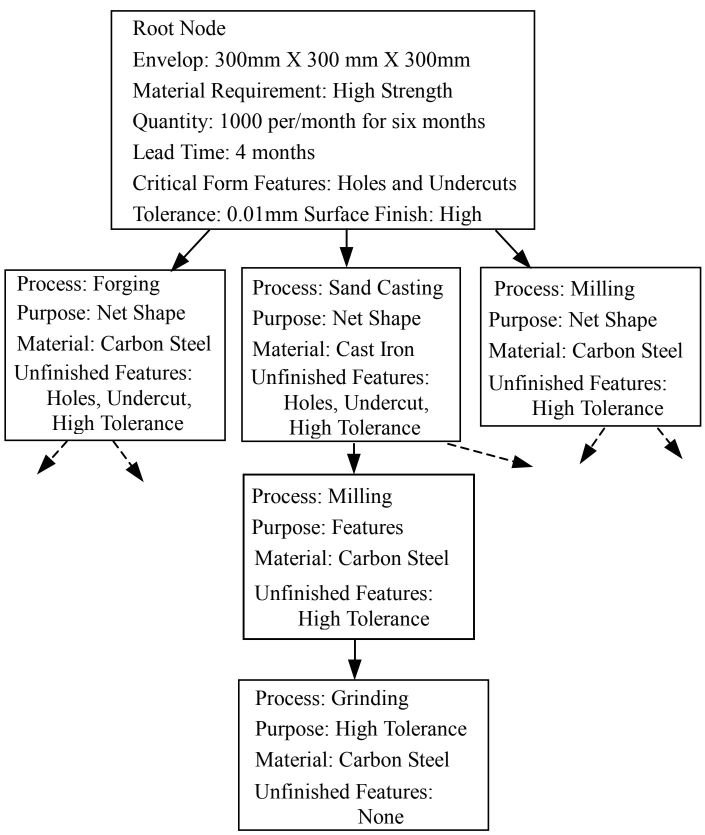

Figure 3: Example of Material/Process Option Tree

Process selection in Step 5a is done in the following manner:

- *Primary Process Selection*: We select the primary processes based on overall gross shape, envelop size, production quantity, and lead-time requirements. We first select a feasible material that satisfies the material requirements. All primary processes associated with each selected material are retrieved from the process database. Then, for each associated process *p*, a high-level feasibility check is performed. Process *p* is infeasible if the production quantity is not feasible (e.g., too high or too low) for *p* or it cannot create the gross shape. Since a primary process may not manufacture the part completely, a list of unfinished design requirements will be maintained in the successor node.
- *Secondary Process Selection*: Secondary processes are used to manufacture any feature(s) that cannot be manufactured by the primary process. All remaining features must be fabricated at this level. Otherwise, a feasible process plan does not exist. Secondary process selection begins with the retrieval of all secondary processes generally associated with the design. Then appropriate processes are selected for features remaining in the unfinished feature lists and are assessed for global feasibility and their compatibility with primary processes.
- *Tertiary Process Selection*: Tertiary processes are used to satisfy surface finish requirements for features which require a finer surface finish than can be provided by the feasible primary and feasible secondary process. For every secondary process with an empty unfinished form feature list and non-empty unfinished tolerance/surface finish list, tertiary process nodes are created and appropriate tertiary processes are selected for the remaining tolerance/surface finish requirements. Tertiary processes are also checked for global feasibility and their compatibility with primary and secondary processes.

5. EVALUATING MATERIAL/PROCESS OPTION TREE AND GENERATING MATERIAL/PROCESS RECOMMENDATIONS

Due to uncertainties in the design requirements at the conceptual design stage, it is not possible to exactly evaluate cost associated with each process sequence option. Please note that such uncertainty is expressed by specifying ranges on design requirement parameters instead of specifying a single value. During evaluation we compute the lower and upper bounds on cost associated with various material/process sequences.

Let *s* be a sequence. We denote the lower bound on the cost associated with *s* by *L(s)*. We denote the upper bound on the cost associated with *s* by *U(s)*. Please note that $U(s) \geq L(s)$. A sequence *s* is said to *dominate* another sequence *s'*, if and only if:

$$U(s) \leq L(s')$$

This condition implies that despite uncertainties, the worst possible outcome for sequence *s* is still better than or comparable to the best possible outcome for sequence *s'*. Therefore, we will always prefer *s* over *s'*.

We use a depth first branch and bound search algorithm to evaluate the option tree. Let *s* be a process sequence that has been already evaluated by the branch and bound algorithm. Any complete or partial process sequence *s'* which is dominated by *s* need not be considered and can be safely pruned. Any process sequence whose cost bounds intersect with the cost bounds of *s* cannot be pruned and will need to be explored.

In the presence of uncertainties, we cannot use 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 *current non-dominated sequence*, if so far during the search no other sequence has been found that dominates this sequence. Let S be the set of current non-dominated sequences. Set S will have the following properties:

1. For every sequence s in S, there is no other sequence s' in S such that $L(s')$ is greater than $U(s)$.
2. For every sequence s in S, there is no sequence s' in S such that $U(s')$ is lower than $L(s)$.

The branch and bound algorithm proceeds in the following manner. Let s'' be a new partial (or full) sequence being considered during the search. If there is at least one s in the set of current non-dominated sequences S such that $L(s'')$ is smaller than $U(s)$, 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, then we examine S to make sure that it still satisfies the two conditions described above. If any solution in S is found to be dominated by another solution in S, then we remove the dominated solution from the set S.

Our branch and bound algorithm does not examine every solution. It uses the above described domination condition as a pruning heuristic to prune unpromising alternatives. The effectiveness of our algorithm depends on how tightly various parameters can be defined during conceptual design stage. If parameters have very large ranges, then very few solutions dominate other solutions and pruning condition does not work very effectively.

After a set of non-dominated solution has been found, we 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. We remove such locally dominated solutions from the set of non-dominated solutions. The remaining solutions are then presented to the designer. If the designer tightens the bounds on some parameter, then we reevaluate solutions and remove the solutions that are dominated.

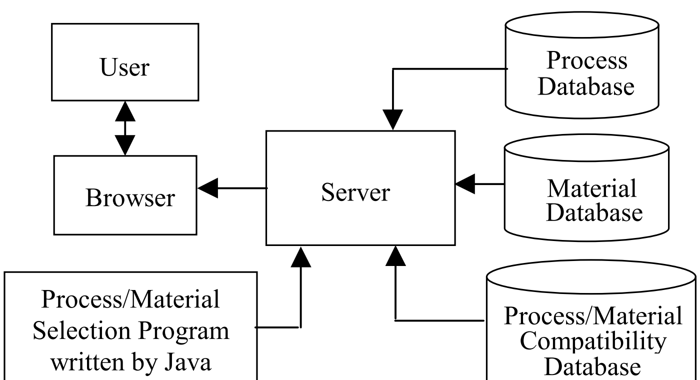

Figure 4: System Architecture

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

6. IMPLEMENTATION AND EXAMPLE

Our system has been implemented using Java. All databases are maintained in Microsoft Access. User can use a browser to connect to our server. Browser automatically downloads the Java program, and it runs in the browser. The user should first input form, business and material parameters describing the conceptual design requirements. After inputting these parameters, our system allows user to select suitable materials and process sequences by searching through various databases using the approach described in Sections 3, 4, and 5. We use SEER-DFM cost estimation software to estimate the cost associated with various process sequences. Our system ranks various sequences and presents its recommendation to the user. Figure 4 shows our system architecture. Figure 5 shows interface of our system.

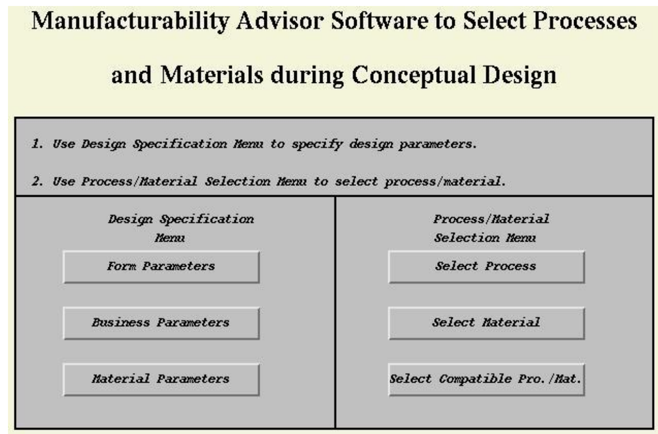

Figure 5: Interface of Our System

6.1 Database Contents

Process database consists of the following fields: process type, process name, feasible production quantity range, minimum lead time, feasible production rate range, form feature list (feature name, feature type, feature size constraints, tolerance, surface roughness), process preconditions. Currently our process database has approximately 40 processes.

Material database consists of the following fields: material type, material subtype, material name, density, yield strength, fracture toughness, young's modulus, hardness, creep strength, CTE (coefficient of thermal expansion), thermal conductivity, resistivity, magnetic property, corrosion resistance, erosion resistance. Currently our material database has approximately 70 materials.

Process/Material Compatibility database consists of the following fields: process name, material name, compatibility status (e.g., infeasible, poor, good, excellent).

6.2 Design Requirements

1. *Form Requirements:* These requirements consist of the following parameters: number of features, feature name, feature type, feature parameters, tolerance, surface roughness, gross shape, envelop.
2. *Business Requirements:* These requirements consist of the following: total production quantity, lead-time, production rate.
3. *Material Requirements:* These requirements consist of the following: density, yield strength, fracture toughness, young's

modulus, hardness, creep strength, CTE, resistivity, thermal conductivity, magnetic property, corrosion resistance, erosion resistance.

6.3 Example

Let us consider conceptual design of a gearbox housing. Various design requirements for this part are given as following:

Business Requirements:

- Production Value: 1000 to 6000 (Please note that range denotes uncertainty in the value of this parameter.)

Form Requirements:

- Gross Shape

Shape: rectangular	Size: 120*110*140mm^3
Wall thickness: 15mm	Tolerance: 0.1-0.5 millimeter
Roughness: 1.6-6.25 micrometer	

- Features: Pocket

depth: 15mm	width: 50mm
length: 25mm	Tolerance: 0.03-0.06millimeter
Roughness: 0.5-1.2 micrometer	

Material Requirements:

- Yield strength/density $\leq$ 20 KPa/kg/m^3
- Creep strength/density $\leq$ 8 Mpa deg C/kg/m^3
- Fracture toughness/density $\leq$ 3 Kpa.m^1/2/kg/m^3
- Youngs molulus/density $\leq$ 3 MPa/kg/m^3

We get the following three non-dominated process sequences for these design requirements:

- *Sequence 1*:
  Material: carbon steel
  Step 1: Milling (Tolerance: 0.0254mm and Roughness: 1.625-----3.175 micron): make the gross shape and pocket feature.
  Step 2: Grinding (Tolerance: 0.0508mm and Roughness: 0.2032---0.8128 micron): improve pocket feature.
- *Sequence 2*:
  Material: carbon steel
  Step1: Forging (Tolerance: 0.762mm and Roughness: 2.285----6.35 micron): make the gross shape and pocket feature.
  Step2: Grinding (Tolerance: 0.0508mm and Roughness: 0.2032---0.8128 micron): improve the pocket feature.
- *Sequence 3*:
  Material: cast iron
  Step1: Sand casting (Tolerance: 3.175mm and Roughness: 7.62-----15.24 micron): make the gross shape.
  Step2: Milling (Tolerance: 0.0254mm and Roughness: 1.625-----3.175 micron): make the pocket feature.
  Step3: Grinding (Tolerance: 0.0508mm and Roughness: 0.2032---0.8128 micron): improve the pocket feature.

We calculated cost for these sequences using by using the SEER-DFM cost estimation tool. Following parameters were used in configuring SEER-DFM tools:

- Weight of raw material: 15lb
- Manufacturing hourly labor rate: 60$
- Number of pattern segments: 2
- Number of cores: 1

Table 2 shows estimated costs produced by SEER-DFM system.

Table 2: Cost of Sequences

Production value (piece)	1000	2000	3000	4000	5000	6000
Sequence1 milling cost ($)	107	107	106	106	106	106
Sequence1 grinding cost($)	8	8	8	8	8	8
Sequence1 total cost ($)	115	115	114	114	114	114
Sequence2 forging cost ($)	182	103	76	63	56	50
Sequence2 grinding cost ($)	8	8	8	8	8	8
Sequence2 total cost ($)	190	111	84	71	64	58
Sequence3 casting cost ($)	35	35	34	34	34	34
Sequence3 milling cost ($)	29	29	28	28	28	27
Sequence3 grinding cost ($)	8	8	8	8	8	8
Sequence3 total cost ($)	72	72	70	70	70	69

These cost are graphically shown in Figure 6. These graph shows that over these range Sequence 3 always dominates Sequence 1. It is not possible to decide between Sequence 2 and 3 unless the uncertainty in quantity is further reduced. By examining the crossover point in more detail, we conclude the following:

- If quantity is greater then 4120 Sequence 2 is preferred.

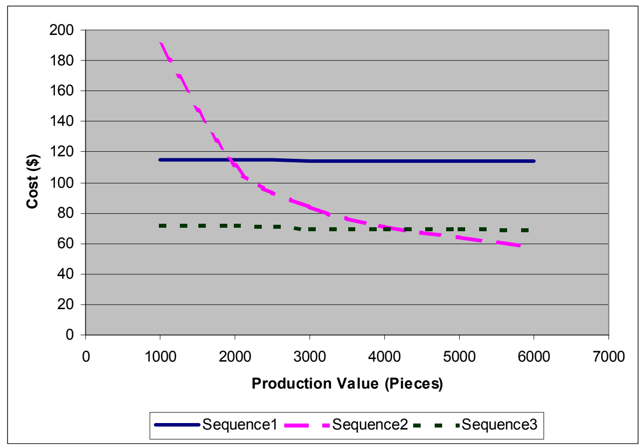

Figure 6: Comparison of Cost Curves for Various Sequences

- If quantity is less then 4120 Sequence 3 is preferred.

7. CONCLUSIONS

In this paper we have described a systematic approach to selecting process/material combination during conceptual design. We follow a two step approach. We first generate an option tree that contains various process/material options. We then evaluate the option tree using a depth first branch and bound algorithm to identify the set of non-dominated process/material combinations. We have implemented our approach in a prototype system. Our system has the following novel features:

1. It accounts for uncertainty in design parameters in selecting process/material combinations.
2. It automatically generates process sequences to satisfy the design 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 standard World Wide Web browser.

4. Databases and algorithms are completely separated. Therefore, as soon as new process/material data is added into the database, it can be used in the selection procedure.

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

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