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ORIGINAL ARTICLE

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A web-based advisory system for process and material selection in concurrent product design for a manufacturing environment

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Abstract This paper reports the work of selecting suitable manufacturing processes and materials in concurrent design for manufacturing environment. In the paper, a fuzzy knowledge-based decision support method is proposed for multi-criteria decision-making in evaluating and selecting possible manufacturing process/material combinations in terms of the total production cost. Based on the proposed method, a prototype Web-based knowledge-intensive manufacturing consulting service system (WebMCSS) with the client-knowledge server architecture is developed to help designers/users find good processes and materials while still at the conceptual level of design. The system, as one of the important parts of an advanced design for manufacturing tool, is a concept level process and material selection tool that can be used as both a standalone application and a Java applet freely available via the Web. Interlinked with Web pages of tutorials, and reference pages explaining the facets, fabrication processes and material choices, the system performs reasoning and calculations using the process capability and material property data from the remote Web-based database and knowledge base that can be maintained and updated via the Internet. The use of the system is illustrated with an example.

Keywords Client-knowledge server architecture · Conceptual design · Design for manufacturing · Fuzzy decision support · Manufacturing advisory system · Process and material selection · WWW

1 Introduction

It is now widely accepted that the final cost of a manufactured product is largely determined at the design stage. When developing a product, 70% of the costs of materials, human labour, and equipment are actually set by decisions made during the conceptual design [1, 2]. Designers will tend to conceive parts in terms of the processes and materials with which they are familiar and may, as a consequence, exclude from consideration process/material combinations that may have proven more economic. A satisfactory method or system for the systematic selection of the suitable process/material combinations for part manufacturing is not currently available. It is thus meaningful to develop such a system in a computer concurrent environment for assisting the designer at early design stages.

The manufacturing consulting or advisory service system may provide a common language for both the designer and the manufacturing engineer who have completely different views on the part to be designed and fabricated at the concept level. The designer has the functional requirements of the part in mind, along with customer needs dimensions, and quantities, but the manufacturing engineer should build tooling and operate production equipment during fabrication. The constraint or conflict can only be resolved when the designer and the manufacturing engineer communicate in the common language, and a shared view of the component must be established [3]. Such systems allow a designer to describe a part so that an expert system can decide which manufacturing processes can produce the desired part in the desired time with the desired quality [3]. This means that it can be designed as a tool for finding a good fabrication method for a part while still at the conceptual level of design. New processes that have yet to achieve the widespread understanding in the engineering community can make their debut through such service system.

With the advent of wide-area networks and the Internet-based Web, a service system can be used to help communicate the abilities of new processes to designers using the Internet [4]. The widespread use of it has led many material suppliers to put database searches online, allowing users to filter inventories based on the user-entered material property ranges. On the other hand, the Internet-based Web allows developers to provide intelligent knowledge-servers [5]. Expert systems running on servers can support a large group of users who communicate with the system over the network. In this approach, the user

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interfaces based on Web protocols provide an access to the knowledge servers. Users do not need special hardware or software to consult these services with the appropriate Web browsers. By implementing an expert system as a knowledge server that performs their tasks remotely, developers can publish expertise on the Web. Technologies and infrastructures that make this approach feasible such as form-based CGI or embedded Java applet in HTML documents are emerging. Expert system technology would also lead to the development of many small and medium-sized advisory systems that could help many categories of novice users in performing the expert-level tasks. As such, it provides an opportunity for making the manufacturing consultation expert system widely available.

This paper aims to develop a Web-based consulting system for selecting suitable manufacturing processes and materials in concurrent design for manufacturing environments:

1. To explore a new knowledge-intensive intelligent methodology for evaluating/selecting manufacturing processes/ materials
2. To develop a new client-knowledge server architecture and framework for manufacturing process/material selection
3. To develop a prototype advisory system for manufacturing process/material selection using Java over the Internet and the Web
4. To integrate the developed manufacturing advisory system into a self-developed concurrent design system

The system is especially dedicated to generating process and material selection advice during embodiment design of mechanical components.

The remaining parts of this paper are organised as follows. The article begins with a review of existing approaches and systems for process and material selection. It then discusses the selection strategy and method. A knowledge-based decision support method is proposed for estimating and ranking possible process and material combinations for a particular component part in terms of total cost. The paper then discusses the implementation of the fuzzy decision support method including the development of a Web-based prototype advisory service system and its use within the context of a "concurrent design for manufacture" scenario, and finally summarises with some conclusions and observations.

2 Literature review

The selection of a suitable process-material pair to manufacture a component or device is not a straightforward matter. There are many factors to be considered. For example, the size of a component, the material to be processed and the tolerance on dimensions. While all processes have slightly different capabilities, there is also a large overlap; for many components there are a large number of processes that would do the job satisfactorily [3].

Software for the process selection stems from the more widespread use of computer tools to assist with material selection. Some more popular commercial tools are documented for material selection [6]. Process selection software tools are more rare than material selection tools such as CAMPS, DA, MAMPS, CES, MAS 1.0 & 2.0 [2, 3, 7–11]. These systems are mainly for common product manufacturing processes and material selection.

Bock [7] described the computer aided material and process selector (CAMPS) as an upgrade of one of the earliest conceptual process selectors, the material and process selector [12]. In CAMPS, a data file is submitted to a series of modules: a fuzzy logic based material exclusion module, and a knowledge acquisition and consultation module that "quizzes" the designer about the part. The user is then presented with two lists that fit all of the requirements: frequently and infrequently used process and material pairs. The final module uses a spreadsheet from [13] to obtain generalised cost estimates for material, tooling, energy usage, and labour.

PSES [10] is a methodical system for generating sequences of processes operating on a single material. It first reduces material options through requirement specification and fuzzy logic set matching. Kunchithapatham [25] created a design advisor (DA) system around separate qualitative material and process searches. In DA systems, the possible material and process lists are reduced in a binary fashion: either they can or cannot meet the requirements. Thus, the user has a list of materials and processes that are unranked – each option is equally valid as far as the DA is concerned. MAMPS, developed by Giachetti [11], is another all-database solution for conceptual process selection. It uses parallel material and process searches, followed by a combination step. All of the results in MAMPS are ranked lists.

The cambridge engineering selector (CES) (http://www.granta.co.uk) is the only commercially available process selection software that contains information of more than 100 different manufacturing processes and process variations. Instead of going through the usual batch input, the user defines the part through a requirement screening sequence. The user graphically defines the upper and lower bound for each requirement – such as surface roughness – and processes whose lines extend above and below the user bounds can meet the current requirement. After the user has stepped through all of the requirements, a final, unranked list of viable processes is generated, by taking the intersection of all the result sets. The user may have many possible processes at each screening step, only to discover that the intersection set has no members. In addition, the CES process search has only a single material requirement. The user selects a material from a list of material groups. For a multi-parameter search of materials, a separate material database must be purchased or self-developed so that the results of the material search can then be matched with the process search to find valid combinations.

The manufacturing analysis service, MAS 1.0 [8] was conceived as a front end for the CyberCut machining service via the Internet-based World Wide Web. It was intended to be a proof-of-concept online process selection tool, using criteria and experience from various sources such as in [14, 26]. While it was the first to bring process selection online, it had a hard coded database, overly simplified material selection, ambiguous requirements, and inconsistent process classification. A second version MAS 2.0 (http://CyberCut.berkeley.edu/mas2/) [3, 15] was developed to fix the problems and extend the scope of the project. In contrast, the MAS 2.0 places the final solution set on screen at all times, allowing the user to observe how a requirement change modifies the final solution set.

3 Manufacturing process and material selection: a knowledge support approach

In this section, a knowledge-based method is constructed using a variety of methods to rank the appropriateness of an option with the value of a requirement. Details about the ranking methods and the knowledge decision support scheme for manufacturing process and material selection are described below.

3.1 Strategy for process and material selection

As stated previously, the selection of a suitable process-material pair to manufacture a component or device is not a straightforward matter. There are many factors to be considered. For example, the size of component, the material to be processed and the tolerance on dimensions. Usually at the beginning of the conceptual design stage, designers are given functional requirements and relevant production 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 envelope size, material requirements, gross shape, form features, tolerances, surface finish requirements, etc. At this stage there exists sufficient information to start preliminary process planning, e.g., material and process selection. The main tasks of the process and material selection is to consider alternative process sequences and compatible materials that can meet the critical design requirements and to select the process sequence that can meet the requirements with the minimum cost. Figure 1 shows a strategy for the process and material selection.

Before discussing the material and process selection at the conceptual design stage two definitions are needed [3]: requirement and option. A requirement is something needed by the emerging design, which may be a material requirement (i.e., hardness), or a process requirement (i.e., production rate, part geometries, size and shape). An option is one of the possible processes (or materials) that the designer is trying to select. Specifically, the design requirements are given as follows [16]:

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

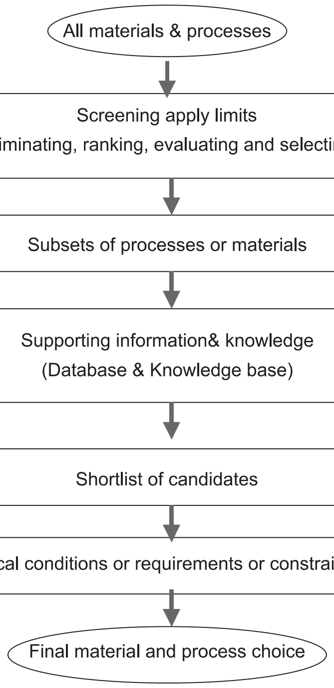


Fig. 1. The strategy for process and material selection

It can be seen that the process requirements can also be classified into form requirements and production requirements. Based on the above design requirements, designers are interested in finding (evaluating and selecting) a process sequence that can meet the design requirements with some criteria and metrics, e.g., the minimum total production cost. The method used in this research is based on the ranking techniques for evaluating and selecting possible process/material combinations for a particular component part in terms of the total production costs. The total production cost C for a sequence S is defined as:

$$C(S) = \sum_{i=1}^{n} C_{P_i} + C_M + \sum_{i=1}^{n} C_{T_i} + \sum_{i=1}^{n} C_{S_i} \qquad (1)$$

where, C_M is the material cost, C_{P_i} is the processing cost associated with the i^{th} process in the sequence (it includes both labour and capital cost), C_{T_i} is the tooling cost with the i^{th} process in the sequence, and C_{S_i} is the setup cost with i^{th} process in the sequence. If there is any imprecision in design requirements, then the total production cost is defined by the cost interval used for describing the minimum and maximum costs associated with a sequence due to imprecision in design parameters.

3.2 Ranking methods and knowledge support scheme

The basic ranking scheme used in the process and material selection is described as follows. The user enters design specifications for one or more requirements. Each possible process/material can then be assigned a requirement rank, based upon the requirement's value. To obtain the ranking for a process, each of its requirement ranks contributes to a weighting function. The output of this weighting function, the figure of merit, is used as the final option rank. The system repeats this for every option each time a requirement value is changed. Each requirement has a method for calculating the rank. The method's parameters are process dependent. A brief description of the methods used in obtaining the requirement ranks was discussed in [3, 30]:

1. Boolean list membership: The option has a list of things it can do. Anything not on the list is impossible for the process to do.
2. Table lookup: For the more complex case of determining material/process compatibility, a two-dimensional array is used to look up a compatibility factor.
3. Integer programming: For qualitative requirements that have value ranges or orders of magnitude, such as production setup time's "hours" or "months". A single integer is used to represent the requirement's value.
4. Trapezoidal fuzzy numbers: Generates a rank for a requirement based upon the design specification and a trapezoidal membership function. This is actually a simplified mode from the fuzzy rank method (see Sect. 3.3 below).

The key elements of a process and material selection tool are composed of database and decision support systems/modules. The database support system communicates to the user with an extensive, up-to-date set of alternatives, while the decision support system concerns itself with evaluation, comparison and selection of alternatives. The decision support system consists of a multi-layered exploration and is knowledge based. Figure 2 depicts a knowledge support scenario of the process and material selection. The user may enter a bare minimum of data, just the batch size or the needed linear tolerance, and get initial feedback about the appropriateness of various manufacturing options. However, should the designer wish to provide more information, they may fill in more requirements. Many of the requirements have an advanced mode to allow the users to more explicitly define their requirements. The kernel of the knowledge based decision support scheme is a (fuzzy) ranking algorithm for the multi-criteria decision-making problems. Details about the fuzzy ranking method will be discussed below.

3.3 Fuzzy ranking method

Due to the uncertainty and fuzziness of design specifications and technical requirements at the early conceptual design stage, it is difficult to assess the process and material performance in this stage. The fuzzy design evaluation and selection technique is used in this research [17]. One of the well-known methods for multi-criteria decision-making is the procedure for calculating a weighted average rating r_i by use of the value analysis or cost-benefit analysis [19]:

$$r_i = \sum_{j=1}^{n} \left(w_j r_{ij} \right) / \sum_{j=1}^{n} w_j \tag{2}$$

where, r_{ij} denotes the merit of alternative a_i according to the criterion X_j; w_j denotes the importance of criterion X_j in the evaluation of alternatives. But this procedure is not applicable for the situations where uncertainty exists and the information available is incomplete, for example, the terms "very important", "good", or "not good" themselves are a fuzzy set. Let a set of

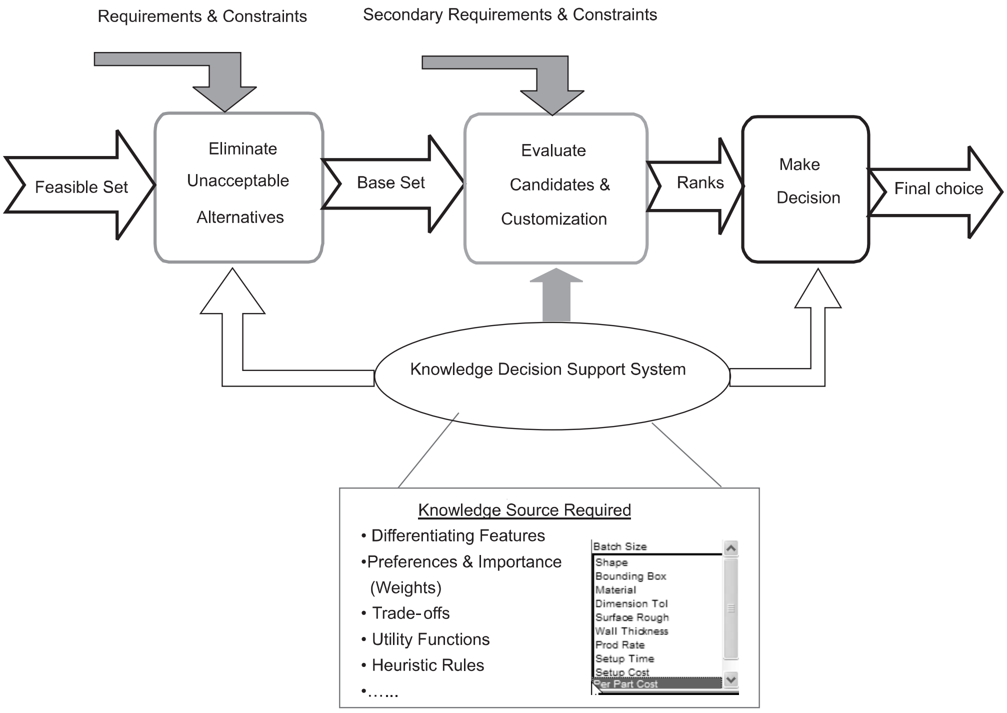


Fig. 2. Knowledge support scenario for process and material selection

m alternatives $A = \{a_1, a_2, \dots, a_m\}$ be a fuzzy set on a set of n criteria $C = \{C_1, C_2, \dots, C_n\}$ to be evaluated. Suppose that the fuzzy rating r_{ij} to certain C_j of alternative a_i be characterised by a membership function $\mu_{R_{ij}}(r_{ij})$, where, $r_{ij} \in R$, and a set of weights $W = \{w_1, w_2, \dots, w_n\}$ are fuzzy linguistic variables characterised by $\mu_{W_j}(w_j)$, $w_j \in R^+$. Consider the mapping function $g_i(z_i) : R^{2n} \rightarrow R$ defined by:

$$g_i(z_i) = \sum_{j=1}^{n} \left(w_j r_{ij}\right) / \sum_{j=1}^{n} w_j \qquad (3)$$

where, $z_i = (w_1 w_2 \dots w_n, r_{i1} r_{i2} \dots r_{in})$. Define the membership function $\mu(z_i)$ as:

$$\mu_{Z_i}(z_i) = \wedge^{o}_{j=1,\dots,n} \mu_{W_j}(w_j) \wedge^{o}_{k=1,\dots,n} \mu_{R_{ik}}(r_{ik}). \qquad (4)$$

Through the mapping $g_i(z_i) : R^{2n} \rightarrow R$, the fuzzy set Z_i induces a fuzzy rating set R_i with a membership function:

$$\mu_{R_i}(r_i) = \sup_{Z_i g(z_i) = r_i} \mu_{Z_i}(z_i), \quad r_i \in R. \qquad (5)$$

Therefore, the final fuzzy rating of alternative a_i can be characterised by this membership function. But it does not mean the alternative with the maximal $\mu_R(r_i)$ is the best one. The procedure needs to further evaluate the following two fuzzy sets [27]:

1. A conditional fuzzy set is defined with the membership function:

$$\mu_{I/R}(i|r_1, \dots r_m) = \begin{cases} 1 & \text{if } r_i > r_k, \forall k \in (1, 2, \dots, m) \\ 0 & \text{otherwise} \end{cases} \qquad (6)$$

2. A fuzzy set is constructed with membership function:

$$\mu_R(r_1, \dots r_m) = \wedge^{o}_{i=1,\dots,m} \mu_{R_i}(r_i) \qquad (7)$$

In this case, a combination of these two fuzzy sets induces a fuzzy set "I", which can determine a best alternative with the highest final rating, i.e.,

$$\mu_I(i) = \sup_{r_1, \dots r_m} \mu_{I/R}(i|r_1, \dots r_m) \wedge^{o} \mu_R(r_1, \dots r_m). \qquad (8)$$

Comparing with Eq. 2, the fuzzy ranking for evaluation and selection is more flexible and presents uncertainty better. Based on this method, the designer can use linguistic rating and weights such as "good", "fair", "important", "rather important", etc., for alternatives evaluation and selection. This is more natural and attractive in practical use.

4 The client-knowledge server architecture and framework

An integrated expert system can be divided into a two-component architecture with a narrow communication channel [5]. Figure 3 illustrates a knowledge-server approach with a separation of the user-interface front end from the problem solver.

In this research, the proposed system architecture and framework adopts the knowledge server paradigm, in which knowledge-based systems can utilise the connectivity provided by the Internet to increase the size of the user base while minimising distribution and maintenance overheads. The knowledge intensive system can then exploit the modularity of knowledge-based systems, in that the inference engine and knowledge bases are located on a server computer and the user interface is exported on demand to client computers via network connections (e.g., Internet, WWW). Thus, modules (objects) are connected together so that they can exchange services to form large integrated system models. The module structure leads itself to a client (browser)/knowledge server-oriented architecture using distributed object technology.

The main system components of the proposed client/knowledge server architecture are shown in Fig. 4. The Java-based

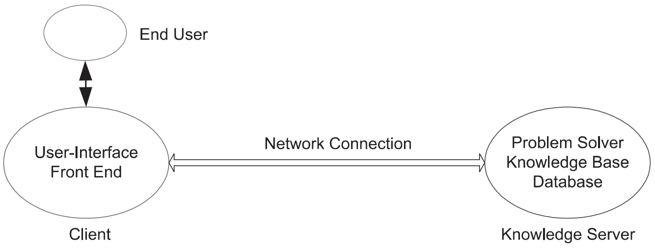
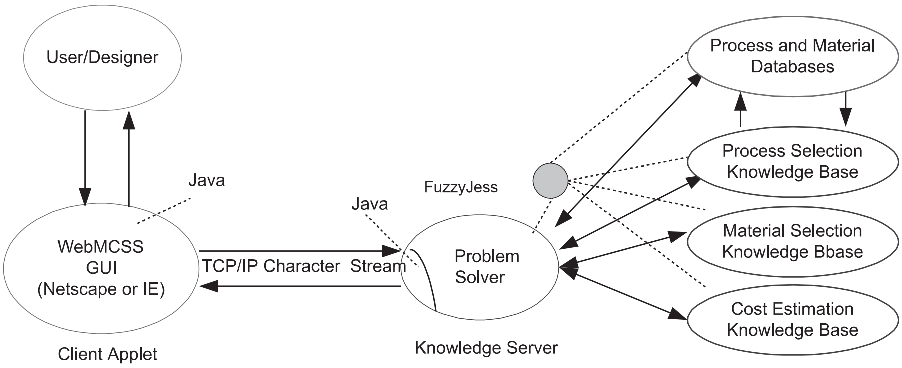


Fig. 3. Client-knowledge server architecture

Fig. 4. The proposed client-knowledge server architecture for MCSS



front end (left) communicates with the knowledge server (right) through a TCP/IP stream. The knowledge server that is Jess-based uses a Java module for communication with the front end. Each of these components interact with one another using a communication protocol (e.g., CORBA) so that it is not required to maintain the elements on a single machine. As a gateway for providing services, the interface of a system component invokes the necessary actions to provide requested services. To request a service, a system component must have an interface pointer to the desired interface.

5 The Web-based manufacturing consulting service system (WebMCSS)

To implement the client-knowledge server framework, a prototype advisory service system, WebMCSS, has been developed. In this section, an overview of its functionality and some implementation issues are discussed.

5.1 Overview of WebMCSS

WebMCSS, is a concept level process and material selection tool for finding a good fabrication method for a part while still at the conceptual level of design. Based on the various input parameters from the design requirements (see Sect. 3.1) provided by the remote designer, WebMCSS can determine which manufacturing processes are most relevant to the inputted part. The goal is to provide the designer with knowledge of the future production requirements of the part. The service provides advice that, first, indicates which manufacturing process is the most suited to the emerging design and, second, how the design could best be modified to satisfy the constraints of that particular process. WebMCSS can also be used as a library of manufacturing techniques since it contains detailed Web sites for manufacturing processes. WebMCSS 1.0 extends FuzzyJess [20, 21] with a graphical user interface (GUI). It can be run as a standalone application or an applet freely available via the WWW and process Jess rule bases that have been modified slightly to work with it. It is interlinked with Web pages of tutorials, and reference pages explaining the facets, fabrication processes and material choices.

WebMCSS performs its calculations using capability data from a remote Web-based database that can be maintained and updated via the Internet. A frame is provided for a first order cost estimation along with examples for selected processes, and provides for the generation of process chains using secondary processes to refine certain features on a part [3]. While running, WebMCSS can generate a dialogue with the designer, inquiring about batch size, typical tolerances, size, overall shape, and cost requirements. After entering values for a set of facets, or attributes, for a conceptual part, the user is given real-time feedback regarding plausible fabrication methods. Once a process is selected, process chains or cost estimates can be explored. At each step along the way, the user is presented with an updated, ranked list of manufacturing possibilities. A similar method is used to define the attributes for material selection (yield strength, density, etc.) and generate material rankings. The final result is a ranked list of viable combinations, obtained through a process-material pair optimisation.

5.2 Implementation of WebMCSS

WebMCSS is a straightforward system that uses a Java program as a front end to an expert system, which was implemented as a knowledge server. We use this system to illustrate the knowledge-server approach and to provide a platform for teaching manufacturing processes and materials, and artificial intelligence and expert systems courses. This knowledge server provides a Web consulting or advisory system for the process and material selection.

Initially, a simple demonstration system was designed as a final-year under-graduate project at the university. It was implemented using the intelligent Web site techniques such as form-based CGI and Javascript. The formal implementation of the system as a knowledge server in Jess/FuzzyJess with a Java front end has several advantages over the original version. Two of the most important are that it runs on standard hardware and is publicly available. Moreover, because Java programs are portable, Web browsers on multiple platforms can run the system. Figure 5 shows a sample applet window from WebMCSS to animate the selection of processes and materials. Figure 6 is a Java application of WebMCSS, which is a local consulting expert system.

WebMCSS communicates with Jess/FuzzyJess through a shared output and input stream. WebMCSS reads from the output stream to which Jess/FuzzyJess writes and then writes to the input stream from which Jess/FuzzyJess reads. This simple interface between Jess/FuzzyJess and WebMCSS allows both applications to evolve independently. Rules that write text to "standard out" will actually write the text into a specific output stream. WebMCSS reads the text string from the output stream, parses it, and directs the information to the corresponding GUI components or performs operations on GUI components. In the same way, rules that read from "standard in" will read text from a specific input stream to which WebMCSS writes the text associated with a particular check box. The text is written to the input stream when the user pushes a button to proceed. The rule base models the reasoning of an expert. At the same time, it determines what information the user of the expert system sees at any given time. Questions, related messages, and possible choices of answers are encoded in a text string that a rule may write to the output stream when it fires. Other rules may expect user input such as the user's answer to a question. The reasoning engine waits until the user selects a possible answer and then pushes "Proceed" (see Fig. 5).

The Java applets allow us to design user interfaces that are more interactive than CGI-based interfaces. This system can also be used as a teaching tool. The purpose is to teach the inexperienced designer/student basic skills in manufacturing processes and materials and interactive rule-based programming and even allow them to experiment with the knowledge-server approach to implementing expert systems. After the designer/student has learned to select manufacturing processes and materials, he/she

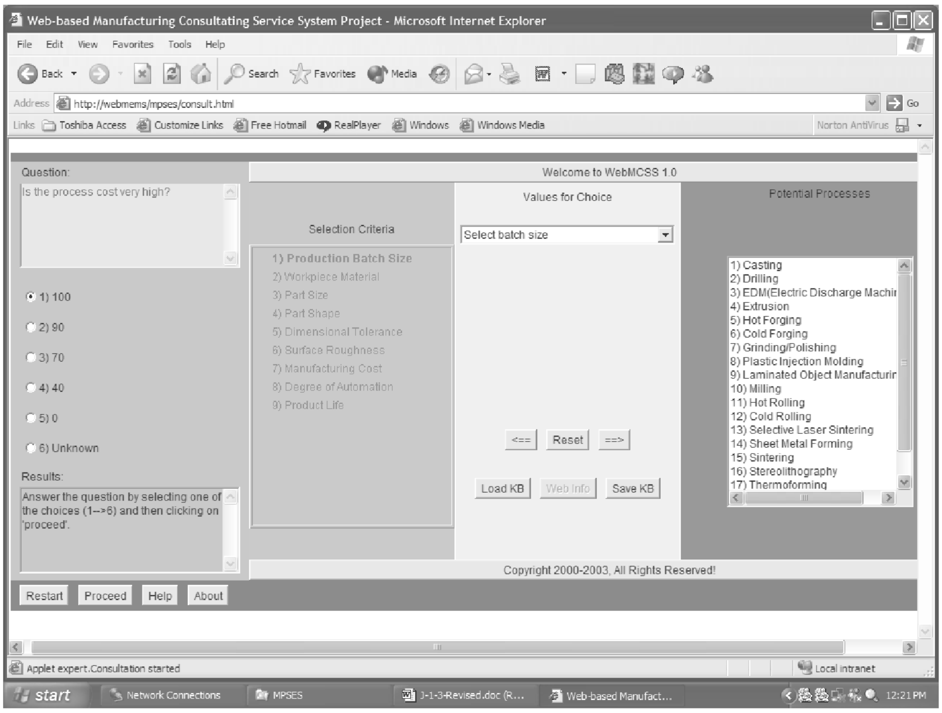


Fig. 5. The applet of WebMCSS

Is the process cost very high?

- ● 1) 100
- ○ 2) 90
- ○ 3) 70
- ○ 4) 40
- ○ 5) 0
- ○ 6) Unknown

Answer the question by selecting one of the choices (1-->6) and then clicking on 'proceed'.

1) Production Batch Size
2) Workpiece Material
3) Part Size
4) Part Shape
5) Dimensional Tolerance
6) Surface Roughness
7) Manufacturing Cost
8) Degree of Automation
9) Product Life

Select batch size

1) Casting
2) Drilling
3) EDM(Electric Discharge Machir
4) Extrusion
5) Hot Forging
6) Cold Forging
7) Grinding/Polishing
8) Plastic Injection Molding
9) Laminated Object Manufacturir
10) Milling
11) Hot Rolling
12) Cold Rolling
13) Selective Laser Sintering
14) Sheet Metal Forming
15) Sintering
16) Stereolithography
17) Thermoforming

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Applet expert.Consultation started

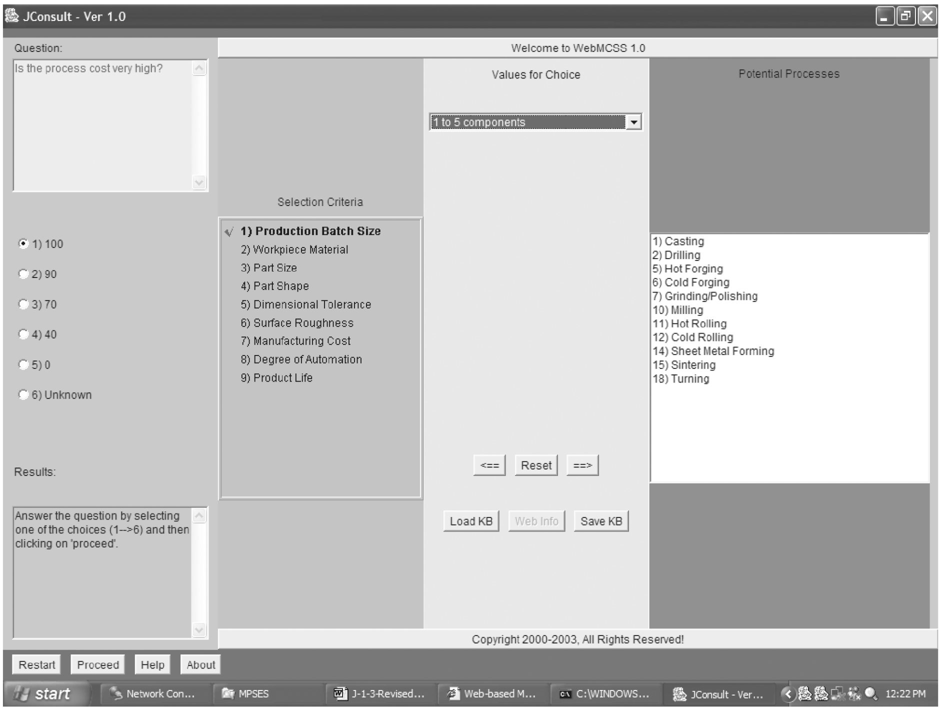

Fig. 6. The stand-alone application version of WebMCSS (JConsult 1.0)

Is the process cost very high?

- ● 1) 100
- ○ 2) 90
- ○ 3) 70
- ○ 4) 40
- ○ 5) 0
- ○ 6) Unknown

Answer the question by selecting one of the choices (1-->6) and then clicking on 'proceed'.

1 to 5 components

✓ 1) Production Batch Size
2) Workpiece Material
3) Part Size
4) Part Shape
5) Dimensional Tolerance
6) Surface Roughness
7) Manufacturing Cost
8) Degree of Automation
9) Product Life

1) Casting
2) Drilling
5) Hot Forging
6) Cold Forging
7) Grinding/Polishing
10) Milling
11) Hot Rolling
12) Cold Rolling
14) Sheet Metal Forming
15) Sintering
18) Turning

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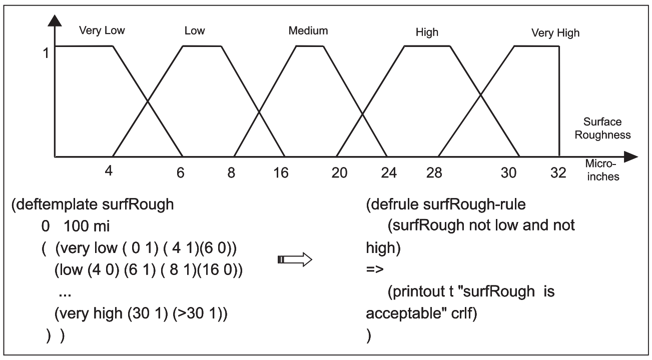
can continue with the design of a small knowledge base that performs this task automatically. Therefore, the designerŠs task can also augment the pre-existing system with appropriate rules that rank and select processes and materials. A sample Jess rule that is compatible with CLIPS rules and used for selecting processes is shown as follows:

```
(deftemplate process
    (slot type)
    (slot value)
)
(deftemplate attribute
    (slot type)
```



```
(deftemplate surfRough
  0   100 mi
  (  (very low ( 0 1) ( 4 1)(6 0))
     (low (4 0) (6 1) ( 8 1)(16 0))
     ...
     (very high (30 1) (>30 1))
   ) )
```

```
(defrule surfRough-rule
    (surfRough not low and not
high)
=>
    (printout t "surfRough  is
acceptable" crlf)
)
```

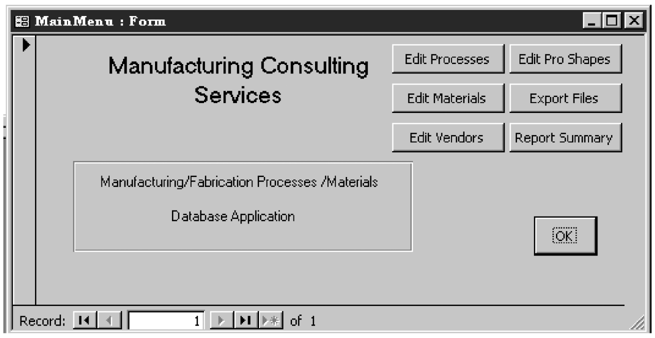
Fig. 7. Fuzzy facts and rule in FuzzyJess

```
    (slot value)
)
(defrule Rule X
    (goal (type identifyProcess) (value "yes"))
=>
    (printout t "Is the process cost high? | explanatory | Answer
                 the question"
                 "by selecting one of the choices (1->6) and then
                 clicking on ’proceed’. |1)100|2)90|3)70|4)40|5)0|
                 6)Unknown |no |end")
    (assert (attribute (type hasHighcost) (value (readline))))
```

Based on the work in [22], the modified Jess rule with certainty factors [100, 90, 70, 40, 0, unknown] (1 → 6) can also play a role in the uncertainty of facts and rules in knowledge representation. This is different from FuzzyJess, but compatible with it. Figure 7 shows fuzzy facts and rules represented in FuzzyJess. To test the selection rules, users can start several simulation rules. In addition to the system knowledge server and its front-end applet user-interface, there is a demonstration applet available publicly. The demonstration applet is self-contained in that it includes a Java-based applet and runs stand-alone without a knowledge server.

5.3 Database and knowledge base for process and material selection

WebMCSS supports many widely used manufacturing processes, such as plastic injection moulding, forging, sand casting, sheet metal forming, extrusion, milling, die casting, shell mould casting, investment casting, and EDM (electrodischarging machining). However, it should include the capabilities of new or less well-known processes at any time if necessary. One of the goals of WebMCSS is to educate a designer or student about new or novel manufacturing methods. On the other hand, one of the criteria used for the development of WebMCSS is to create a repository of manufacturing data separate from the code for the main program. This remote process-capability database contains information about the component processes, materials, and vendors. Microsoft Access was used to develop the relational database. Opening the database on the server brings up a menu of tools [3, 17] described here. (1) Vendor Editor provides the account management for companies that have processes; (2) Material Editor: Edit the properties of the generic raw materials; (3) File Exporter: Generates data files and human readable reports; (4) Process Editor: Specifies the performance of all processes, compatibilities with materials, and locations of online resources. These tools can add a new process or material to WebMCSS without any changes to the compiled code. JDBC is chosen as the method for implementing remote vendors that access to content in WebMCSS databases (Fig. 8). A Java database system was developed by making use of a Microsoft Access database to store the detail information of processes and materials and a Java program to access the database through a JDBC connection. Figure 9 shows a pictorial view of Java database system scheme. The design of Java interfaces (applet) was proven to be the most extensive part of the project (Fig. 10). The Java applets were developed as well to access the database from an Internet browser. The knowledge base is actually a rule base to choose manufacturing processes and materials constructed using Jess/FuzzyJess. Figure 11 shows the system loading an external knowledge base.



Manufacturing Consulting Services

Manufacturing/Fabrication Processes /Materials

Database Application

Fig. 8. Process capability and material database administrator tools

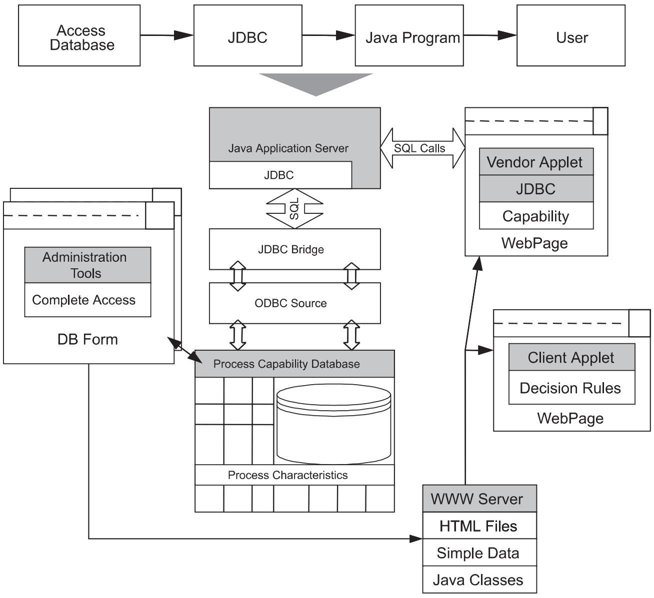
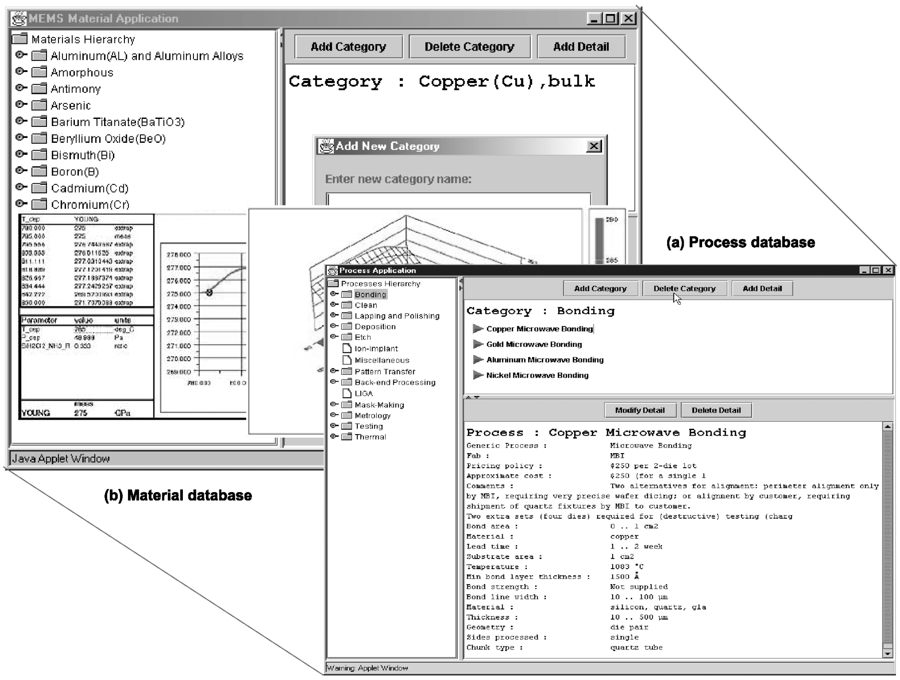


Fig. 9. Java database system scheme



Category : Copper(Cu),bulk

Category : Bonding

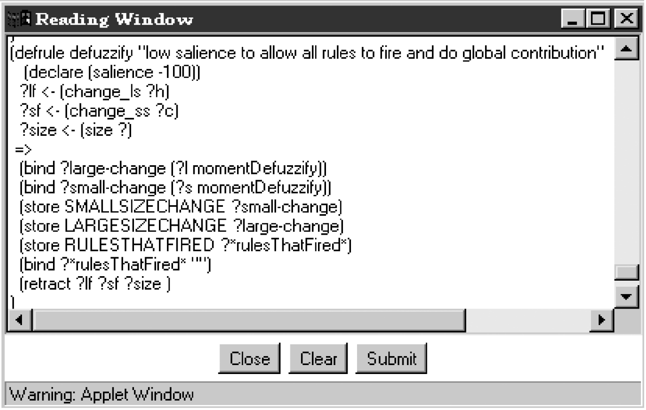
- Copper Microwave Bonding
- Gold Microwave Bonding
- Aluminum Microwave Bonding
- Nickel Microwave Bonding

```
Process : Copper Microwave Bonding
Generic Process :            Microwave Bonding
Fab :                        MBI
Pricing policy :             $250 per 2-die lot
Approximate cost :           $250 (for a single 1
Comments :                   Two alternatives for alignment: perimeter alignment only
by MBI, requiring very precise wafer dicing; or alignment by customer, requiring
shipment of quartz fixtures by MBI to customer.
Two extra sets (four dies) required for (destructive) testing (charg
Bond area :                  0 .. 1 cm2
Material :                   copper
Lead time :                  1 .. 2 week
Substrate area :             1 cm2
Temperature :                1083 °C
Min bond layer thickness :   1500 Å
Bond strength :              Not supplied
Bond line width :            10 .. 100 µm
Material :                   silicon, quartz, gla
Thickness :                  10 .. 500 µm
Geometry :                   die pair
Sides processed :            single
Chunk type :                 quartz tube
```

(a) Process database

(b) Material database

Fig. 10. Process and material database Java applet launched



```
)
(defrule defuzzify "low salience to allow all rules to fire and do global contribution"
   (declare (salience -100))
  ?lf <- (change_ls ?h)
  ?sf <- (change_ss ?c)
  ?size <- (size ?)
 =>
  (bind ?large-change (?l momentDefuzzify))
  (bind ?small-change (?s momentDefuzzify))
  (store SMALLSIZECHANGE ?small-change)
  (store LARGESIZECHANGE ?large-change)
  (store RULESTHATFIRED ?*rulesThatFired*)
  (bind ?*rulesThatFired* "")
  (retract ?lf ?sf ?size )
)
```

Fig. 11. Loading of external knowledge base

5.4 Integration with the concurrent collaborative design system

WebMCSS is developed mainly for intelligent traditional manufacturing process and material selection on the Web. It is also incorporated as a sub-system into a concurrent collaborative design system, WebKIDSS [23], which is currently being developed. WebKIDSS has a unique combination of manufacturing and CAD that allows the incorporation of true process data into the fabrication simulation. A comprehensive materials database available [18] provides a vital link between the process parameters and the device behaviours and performances.

The difficulties of integrating WebMCSS in CAD/CAM systems are related to the geometry-based process selection, which have to leverage existing group technology research to relate between bridge level design features and manufacturing processes [3]. One of the most frequently encountered problems is a misclassification of shape. This problem could readily be circumvented if the user were able to submit a solid CAD model. As computers become faster, and manufacturing feature recognition systems become more developed, a future WebMCSS might accept a CAD model as input. The main barrier to the realisation of a CAD/CAM integrated WebMCSS is general feature recognition. Existing feature recognition schemes are mostly geared toward a specific manufacturing process [24]. All of the WebMCSS processes would need adequate feature recognition programs set up to extract the manufacturing features, which may differ for each process. Once this set of features has been extracted, tests for manufacturability can be run. Currently, recognition algorithms and feature based manufacturability tests do not exist for all of the processes included in the WebMCSS. Mesh generation algorithms are demonstrated to move towards general feature recognition.

6 Support and use of WebMCSS

In this section, we will discuss how to use WebMCSS for manufacturing process and material selection, which is also used to verify the developed method and system discussed above.

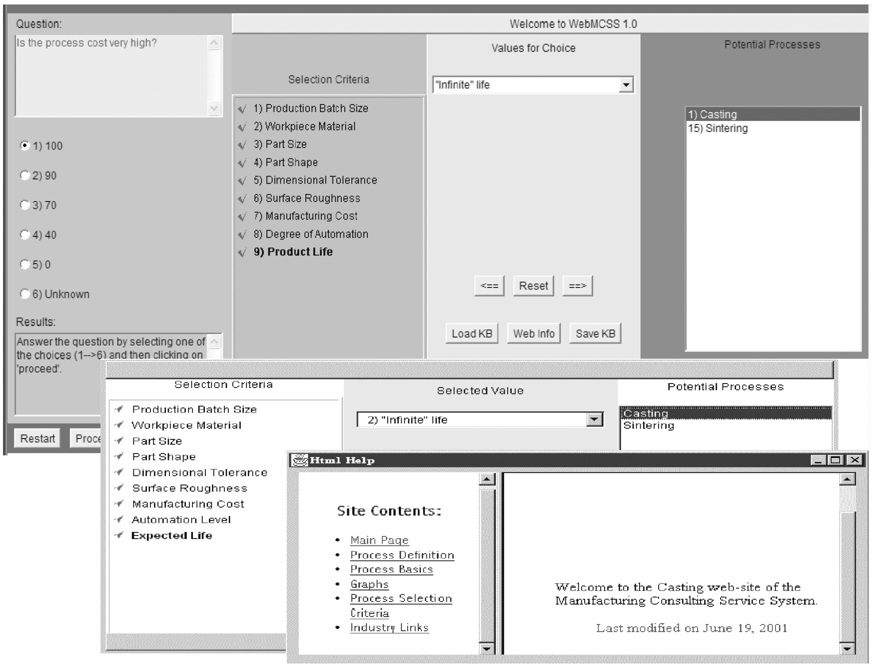
6.1 Supporting WebMCSS

A step-by-step tutorial provides instructions to users/students who are not familiar with manufacturing terms. Descriptions and sample values are given for each of the process and material requirements, allowing users to compare their tolerancing values with common products. Each of the processes included in WebMCSS has a set of descriptive Web pages. The information includes production numbers, shape capabilities, design rules, sample parts, material usage notes, pros/cons, related processes, and links to equipment suppliers and fabrication sites. All of the documentation is linked through the applet itself. The designer may select any process, material, or requirement, and click the "Web Info" button to call up an informational Web page. The instructions of the system can be described as follows [26, 29]:

1. At the beginning of an analysis, the designer/user should select the appropriate value for the batch size range (i.e., production volume) for the part in question.
2. After selecting a value of batch size, the other process selection criteria in the list become active, and the designer/user can then select any property at left and its appropriate value in the centre menu.
3. Continue specifying the selection criteria values until the designer/user has defined as many properties as desired.
4. After each definition of a process selection criterion, the process list at the right will be automatically updated to show the list of processes relevant to the current set of the imposed selection criteria.
5. The designer/user can make changes or input additional selection criteria until the list of compatible processes has been reduced to a point at which the user feels comfortable making a process decision.
6. To remove an imposed selection criterion, click on the relevant checkmark.
7. To access a process Web site, double-click on the process name in the right-hand list or highlight the process and click the Web Info button.
8. If necessary, the user can interactively load external knowledge base(s) for a specific selection problem. This gives the designer/user intuitive understanding of the selection of manufacturing processes and materials.
9. In all above steps, rules in the knowledge base may expect user input such as the user's answer to a question. The reasoning engine waits until the user selects a possible answer and then pushes "Proceed".

6.2 Illustrative example

This example illustrates the use of the WebMCSS for exploring the possibilities for making a full production run of a sample product (e.g., gearbox). The part (e.g., gear) would be subject to real use. Thus, it is necessary to use both the process search and the material search. The following specifications are used for the processes. The selection criteria and values are as follows. (1) Production batch size (volume): 300 000; (2) Workpiece material: steel; (3) Part size: medium; (4) Part shape: irregular or complex shape; (5) Dimensional tolerance: > 0.005; (6) Surface roughness: > 32 micro-inches; (7) Manufacturing cost: high; (8) Automation level: some automation; and (9) Expected life: infinite life. The potential output processes are: casting (1.00), and sintering (0.90). Using this system, the user can observe and select the processes interactively. For example, if the material is chosen as plastics under the condition that there is no change for other specifications, then the output process will be molding/casting. Similarly, if the part shape is thin walled parts, and then the output process is changed into either casting or sheet metal forming accordingly. The search was for the lowest possible cost over a long production cycle. At the end of the process search, casting (rank 1.00) was ahead of the only other possibility: sheet metal forming (rank 0.92). Figure 12 shows the search process with a Q&A mode and a summary of the viable



Is the process cost very high?

● 1) 100
○ 2) 90
○ 3) 70
○ 4) 40
○ 5) 0
○ 6) Unknown

Answer the question by selecting one of the choices (1-->6) and then clicking on 'proceed'.

✓ 1) Production Batch Size
✓ 2) Workpiece Material
✓ 3) Part Size
✓ 4) Part Shape
✓ 5) Dimensional Tolerance
✓ 6) Surface Roughness
✓ 7) Manufacturing Cost
✓ 8) Degree of Automation
✓ **9) Product Life**

"Infinite" life

1) Casting
15) Sintering

✓ Production Batch Size
✓ Workpiece Material
✓ Part Size
✓ Part Shape
✓ Dimensional Tolerance
✓ Surface Roughness
✓ Manufacturing Cost
✓ Automation Level
✓ **Expected Life**

2) "Infinite" life

Casting
Sintering

Site Contents:

- Main Page
- Process Definition
- Process Basics
- Graphs
- Process Selection Criteria
- Industry Links

Welcome to the Casting web-site of the Manufacturing Consulting Service System.

Last modified on June 19, 2001

Fig. 12. Final selection results

materials and processes. Casting with steel is the best choice, with sheeting metal forming being second best.

7 Summary and future work

WebMCSS uses the Internet to bring together engineering reference material and an informative educational or learning tool. The reference material includes basic process descriptions, special abilities, some simple design rules, and links to fabrication sites. WebMCSS provides a knowledge intensive intelligent dynamic environment for designers/students about the trade-offs available in different manufacturing processes. The applet is available to anyone with a Java compatible browser, in order to work in most computing environments. The tool can be used for both simple parameter searches to select process and complex process and material combined searches with secondary processes mapped to high-tolerance features in concurrent product design for manufacturing. It can also be embedded into a concurrent design system or CAD/CAM system. The underlying database and knowledge base are extensible through a set of administrator tools or via the Web, which gives commercial manufacturing facilities the ability to update their own processes and rules. The designer/student can also submit online external manufacturing process and material selection knowledge bases for some specific new processes. Future work will focus on improving the method and the system. It may also be required to tailor or extend the ability of the system for some specialised applications such as concurrent design for MEMS (micro-electro-mechanical systems) devices [28].

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