A Knowledge-based Decision Support System for RP&M Process Selection

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Abstract

Due to the large variety of RP&M material/machines and the strengths/weaknesses associated with different RP&M processes, the decision to select a suitable RP&M system becomes increasingly difficult. This paper presents a knowledge-based approach for the selection of suitable RP&M material/machine to meet specific requirements of RP&M applications. The system receives input data on the CAD model and the user's specifications, and generates outputs that provide the most appropriate combination of RP&M material/machine. Optimal orientations, together with estimated manufacturing time and cost, are considered and given in the final outcome to help the user make the choice.

1. Introduction

In the past decade, the world has seen a rapid growth of RP&M technology: new RP&M processes have been initiated; dimensional accuracy and material properties of RP&M parts have improved; application fields of RP&M parts are expanding. At present there are more than 30 kinds of RP&M machines available in the market. Most of the commercialized RP&M machines can handle more than one kind of materials, with some having four or five choices. For each set of RP&M material and machine, there exists optimal process parameter settings, or optional building styles, for part fabrication. The large variety of RP&M material/machines plus the individual strength/weaknesses with the different RP&M processes make the selection of suitable RP&M system a difficult task (Loh *et al* 1998). Meanwhile, as a group of rapid prototyping facilities, RP&M machines play the role of a bridge between computer-aided design and manufacturing activities. A software tool that enables designers or engineers to select the right RP&M material, machine and optimal orientation for a given RP&M application would thus be essential and useful, helping to shorten the time between design and manufacturing activities further.

The difficulties on the task of selecting suitable RP&M machine for a specific part fabrication have been noticed by other researchers (Grimm 1996, Campbell and Bernie 1996, Phillipson and Henderson, 1997, BIBA WWW, 1998). Grimm outlines a number of guidelines on the choosing between SLS and SLA for a specific part fabrication. Campbell and Bernie proposed the setting up of RP&M machine databases in term of machine capabilities in constructing different types of form features. The evaluations of manufacturing time/cost with a certain RP&M system for a given CAD model are not addressed in the paper. The Phillipson paper describes their RP Advisor that helps the user select RP&M machine. The selection of material was not considered in the software. A software tool called Rapid Prototyping System Selector has been found on the web (BIBA WWW, 1998). Developed on a RDBMS, the RP System Selector find the suitable rapid prototyping system by calculating the degree of fulfilment of each system with respect to the vector of user's requirement. The influence of part geometry on the building quality was not considered. In this paper, we present a knowledge-based approach in the selection of RP&M process.

2. Knowledge-based RP&M Process Selector

2.1 Information Requirements of RP&M Material/Machine Selector

The selection of RP&M material/machine is a high-level decision-making process, requiring extensive knowledge and expertise on RP&M processes. Factors considered usually include manufacturing time, manufacturing cost, the part geometry, the RP&M material properties, the process capabilities and the user requirements on material properties, surface finish, functional purpose, etc. Basically, the process-related information can be categorized into following fields:

1) RP&M material data, including the mechanical, thermal and chemical properties of the material, the cost of material, the physical appearance, etc.;
2) RP&M machine data, including the feasible materials, the building style, the controllable process parameters, the machine capabilities, etc.;
3) RP&M application data, supplying typical application-related requirements on material property, tolerance, surface finish, etc.;
4) Geometric data, providing information such as the part envelope, the part volume, the smallest linear dimensions, the types of form features, etc.;
5) Model specification, including application purpose, dimensional tolerance, general surface finish, material properties, etc.

These five fields define the five highest-level clusters of information needed in RP&M process selection. The information achievable can be in the form of facts, experimental data, or numerical models. Based on the information, process-related decisions can be made for the fabrication of the RP&M part, as illustrated in Figure 1.

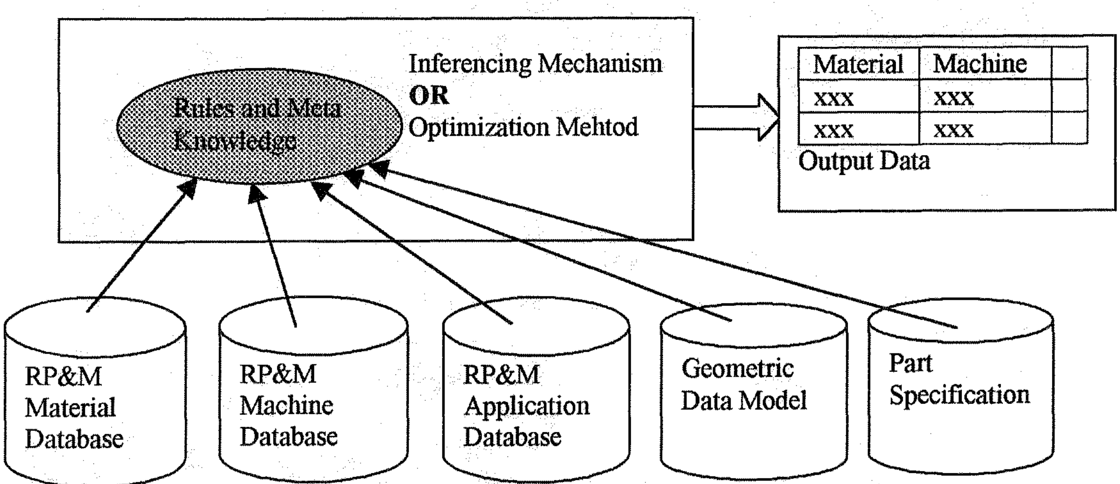


Figure 1 Information Requirements in RP&M Material/Machine Selector

2.2 Feasibility of Knowledge-based RP&M Process Selector

The selection of RP&M material/machine involves large amount of information. Also, to make decisions properly, the prototype requirements or the part specification must be first refined into low-level goals. Since different objectives required of an RP&M part/prototype may be conflicting when detailed into low-level tasks, meta-knowledge is needed to control the decision flow in the execution of tasks. The interdependent relationships among the manufacturing quality, the manufacturing time/cost and the part geometry, plus the non-procedural characteristic of the selection process suggest the suitability of employing knowledge-based approach in the system. The separation of knowledge from the inference mechanism allows the process-related knowledge to be easily modified and supplemented.

3. Object-oriented Data Organization

As a design approach, object-oriented design encompasses the process of object decomposition and depicts a complex system from the perspectives of classes, attributes and methods (Booch, 1991, Cattell, 1991, Yourdon and Argila, 1996). In the domain of RP&M, a common nature of RP&M machines is using additive methods to construct 3-dimensional solid objects. The hierarchy and similarities among RP&M machines as well as the reoccurrence of application cases, show the feasibility of an object-oriented design in the system.

3.1 RP&M Material Database

The compilation of a comprehensive RP&M material database is useful for the management of the variety in the material domain. In the family of RP&M material, a number of abstractions are defined to facilitate the management and selection of RP&M material. As illustrated in Figure 2, the highest level of abstraction is named as *RP&M material*, which is further inherited by four child abstractions, namely *Ceramic-based*, *Plastic-based*, *Metal-based* and *Fibre-based*. Each specific RP&M material in the material database is declared as an instance of certain class. The class attributes and member functions are shown in Figure 3.

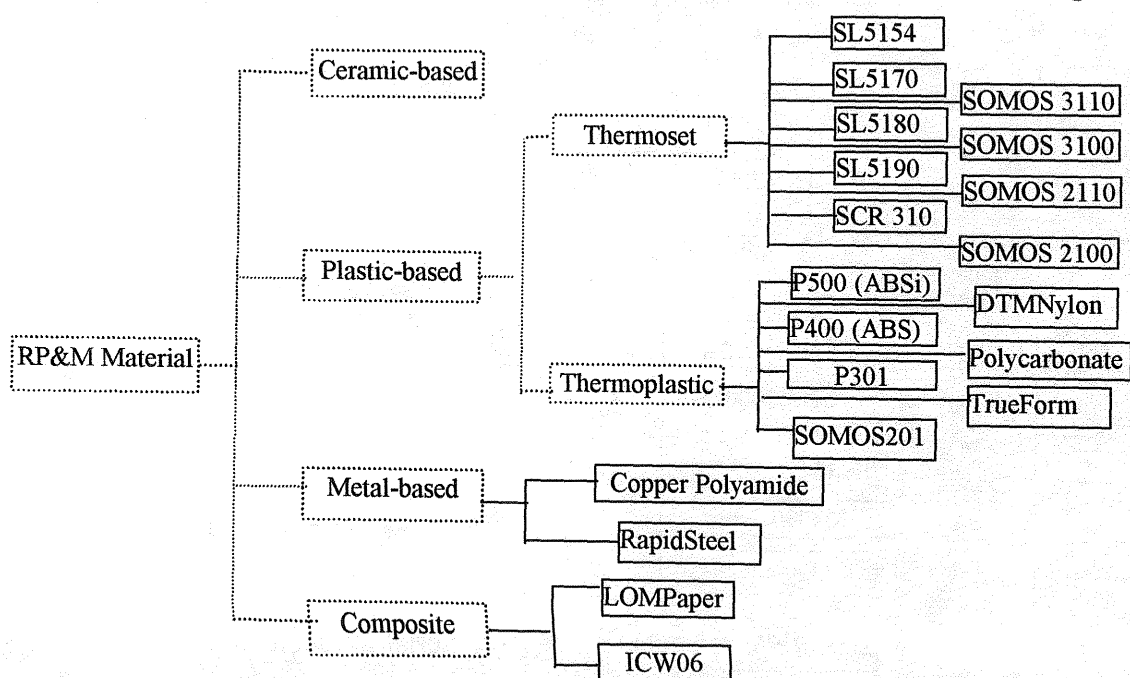


Figure 2 Hierarchy and Abstractions in the Field of RP&M Material

3.3 RP&M Machine Database

The RP&M machine database should give information on the underlying process, the process characteristics, machine parameters, material types feasible on the machine, part building styles and machine capabilities on dimensional accuracy, surface finish, etc. Object-oriented technique is used to organise facts and knowledge inherent to RP&M machines. The hierarchy in the domain of RP&M machine is shown in Figure 3, where the rectangle in dotted line indicates an abstraction while the rectangles in solid line indicate objects, or specific RP&M machines.

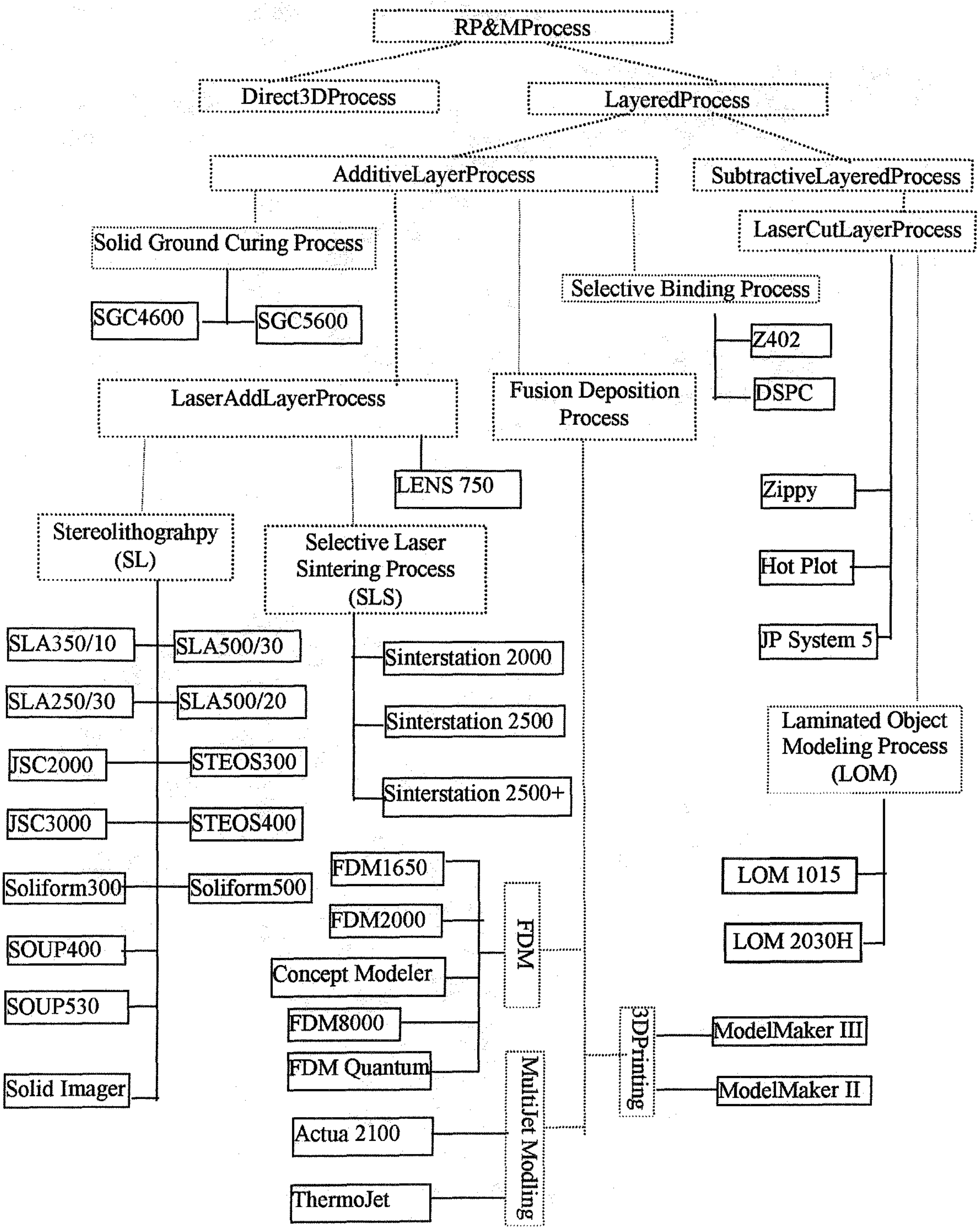


Figure 3 Hierarchy and Abstractions in the Family of RP&M Machines

3.4 RP&M Application Database

The construction of RP&M application database can help users trace the previous RP&M applications and reduce the user's efforts on the definition of part specification. The application of RP&M parts can be classified into three categories: visualization prototype, functional part/prototype and manufacturing tool. For each category applications, the range of the general requirements on the geometric quality, mechanical property or thermal property may be defined. *RP&M Application* is created as the highest-level abstraction in the application domain. Under the base class, three abstractions, namely *VisuModel*, *FunctionPart* and *ManuTool*, are defined to represent the aforementioned three categories of RP&M applications. In the category of *ManuTool*, different applications can be defined based on the follow-up manufacturing processes when a process chain is involved in the tooling process.

3.5 Part Definition

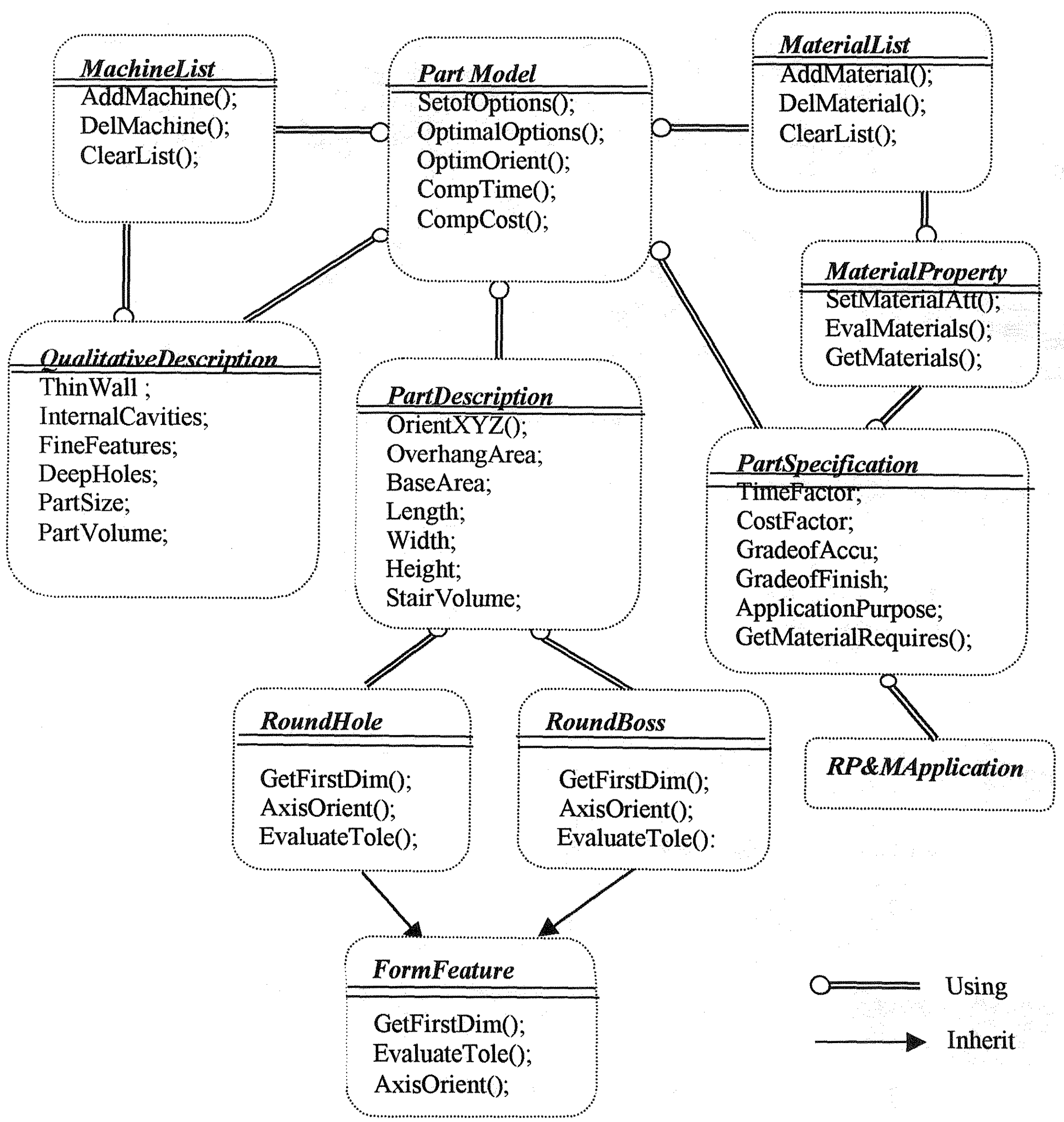


Figure 4 Object-oriented Representation of the Product Model

Development of an object-oriented representation for the product model is an important task in the research. To satisfy the information requirements in the knowledge-based RP&M process selector, the part definition should include both geometric characteristics of the CAD model and the non-geometric aspects. A high-level abstraction called *Part Model* is defined to capture each specific CAD model. The *Part Model* has five internal objects, i.e. *Part Specification*, *Part Description*, *Qualitative Description*, *Machine List*, *Material List*, and has using relationship with objects such as *RP&M Process*, *RP&M Material* and *RP&M Application*, etc. as shown in the diagram in Figure 4. The abstraction of *Part Specification* encapsulates information on material requirements, dimension tolerance, surface finish, application purpose, while the *Part Description* gives information on the geometric attributes of the CAD model in a specific orientation. The abstraction of *Qualitative Description*, on the other hand, encapsulates the general qualitative description of the part shape given by the user.

4 Knowledge-based RP&M Material/Machine Selection

Besides facts and procedural knowledge, empirical knowledge also play important roles in the selection of RP&M material and machine. The factual knowledge related to the selection of RP&M material/machine are stored in the database. The procedural and empirical knowledge, on the other hand, are expressed as method functions or organised into rule sets according to the tasks and the object they work on.

4.1 Knowledge Acquisition and Representation

The selection of RP&M material/machine for a specific part fabrication relies on both numerical evaluation and expertise-based guidelines. The evaluation relates to the examination of material property, the building envelope, the building accuracy of critical features, etc. The guidelines refer to the high-level heuristic knowledge and the controls required in the selection of RP&M process. To acquire knowledge, experiments and interview with experts have been carried on. Mathematical models on computing manufacturing time and cost in RP&M part fabrication are also established.

Evaluations and expertise-based guidelines are expressed in the format of production rules and invoked from the methods of corresponding objects in the system. According to the functionality, the production rules are organised into three rule sets, named as *Material Evaluations*, *Process Guidelines*, and *Machine Evaluations*, respectively. The rule set of *Material Evaluations* includes rules related to the task of material selection or material property evaluation. Rules that summarise experts' experience and reflect the limitations of generic RP&M processes are collected in the rule set of *Process Guidelines*. Rule_1 and Rule_2 are two examples in the rule set of *Material Evaluations*.

Rules1a in *Material Evaluations* {
If:
?application = PartSpecification.ApplicationPurpose; /*get the application purpose */
?user_hardness = PartSpecification.Hardness;
?user_hardness = = NULL; /* the user don't specify the requirement on hardness */
Then:
MaterialProperty.Hardness=?application.Hardness; /* the hardness requirement in the application database is retrieved */
}

```
Rule1b in MaterialEvaluations {
If:     ?hardness=MaterialProperty.Hardness; /* Obtain the attribute value */
        ?hardness!=NULL;    /*
        PartModel.MaterialList != `( ); /*there are material candidates available */
Then:   for ?material inlist PartModel.MaterialList  /* Check material one by one */
{       if ?material.Hardness< part_hardness;
        then PartModel.MaterialList -== ?material;
        }/* Material whose hardness is lower than that required is removed */
}
```

In the rule set of *Machine Evaluations*, the resolution of the RP&M building system, the dimensional accuracy of critical features and the building envelope of the part are examined. RP&M machines that satisfy both the accuracy requirement of the critical form features and the physical requirements of the fabricating part are found out and chose as the suitable machines.

4.2 Framework of Object-oriented Knowledge-based RP&M Process Selection

The object-oriented knowledge-based RP&M material/machine selector is designed to work with a 3D CAD system. The interface and the working mechanism of the object-oriented knowledge-based RP&M material/machine selector is illustrated in Figure 9.

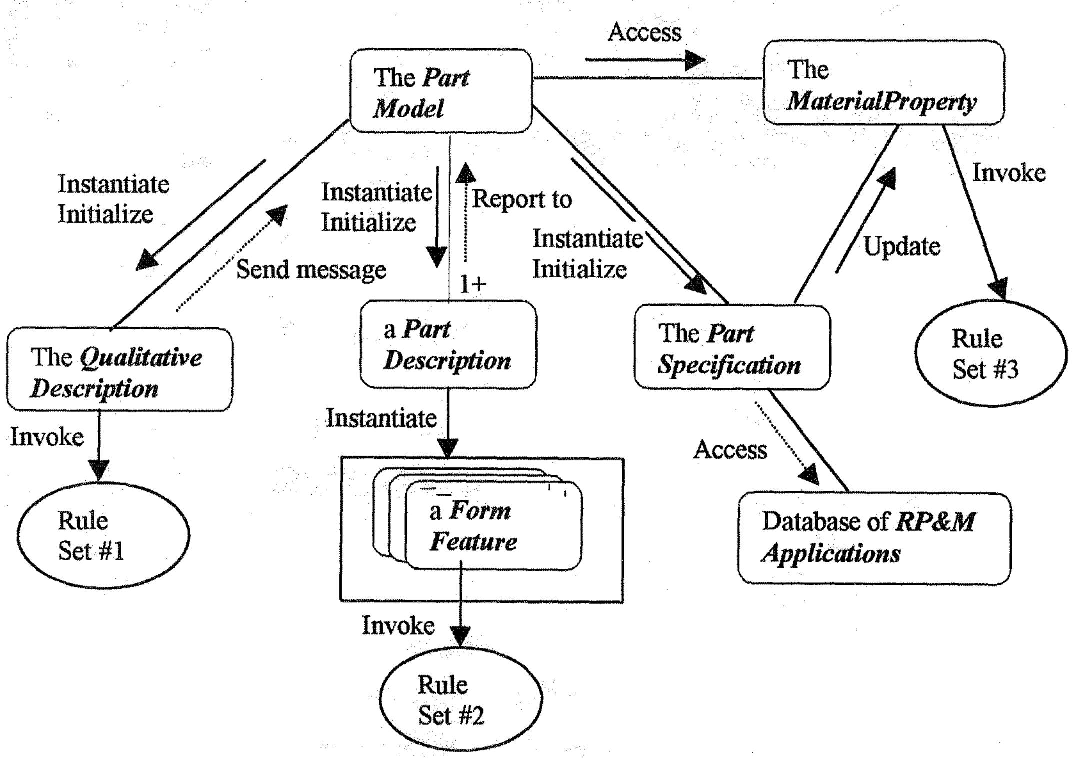


Figure 5 Object Diagram of the Knowledge-based RP&M Material/Machine Selector

Based on a given CAD solid model, a *Part Model* object is first created. The initializtion of the *Part Model* object simultaneously instantiates the objects of *Qualitative Description*, *Part Specification* and *Part Description*, *Machine List*, *Material List*, etc., as illustrated in Figure 5. All the RP&M material available in the database is assigned to *Material List* in the initialisation. The material-related rule-sets are activated from the method function of the *Part Specification* object. RP&M materials that do not satisfy the application requirements on material would be removed from the *Material List* via the firing of rules. Similarly, the chaining in the rule sets of *Process Guidelines* and *Machine Evaluations* would guarantee the selection of RP&M machines that satisfy the application requirements on the building quality and the manufacturing cost. Numerical procedures, such as the computation of manufacturing time, the computation of manufacturing cost, the optimal orientation determination, are implemented in the method functions of the *part model*.

5 Implementation and Case Study

A prototype based on the proposed object-oriented model has been developed using Kappa, a knowledge-based application development platform. The commercial object-oriented developing platform together with its inherent data management functionality reduces the amount of development efforts required. The main screen of the prototype is shown in Figure 6. The implemented RP&M material/machine selector can serve as a software tool assisting the designers in the selection of appropriate RP&M machines in the product development cycle. Geometric data of a CAD model needed in the knowledge-based system is extracted from the CAD model database and passed to the knowledge-based system.

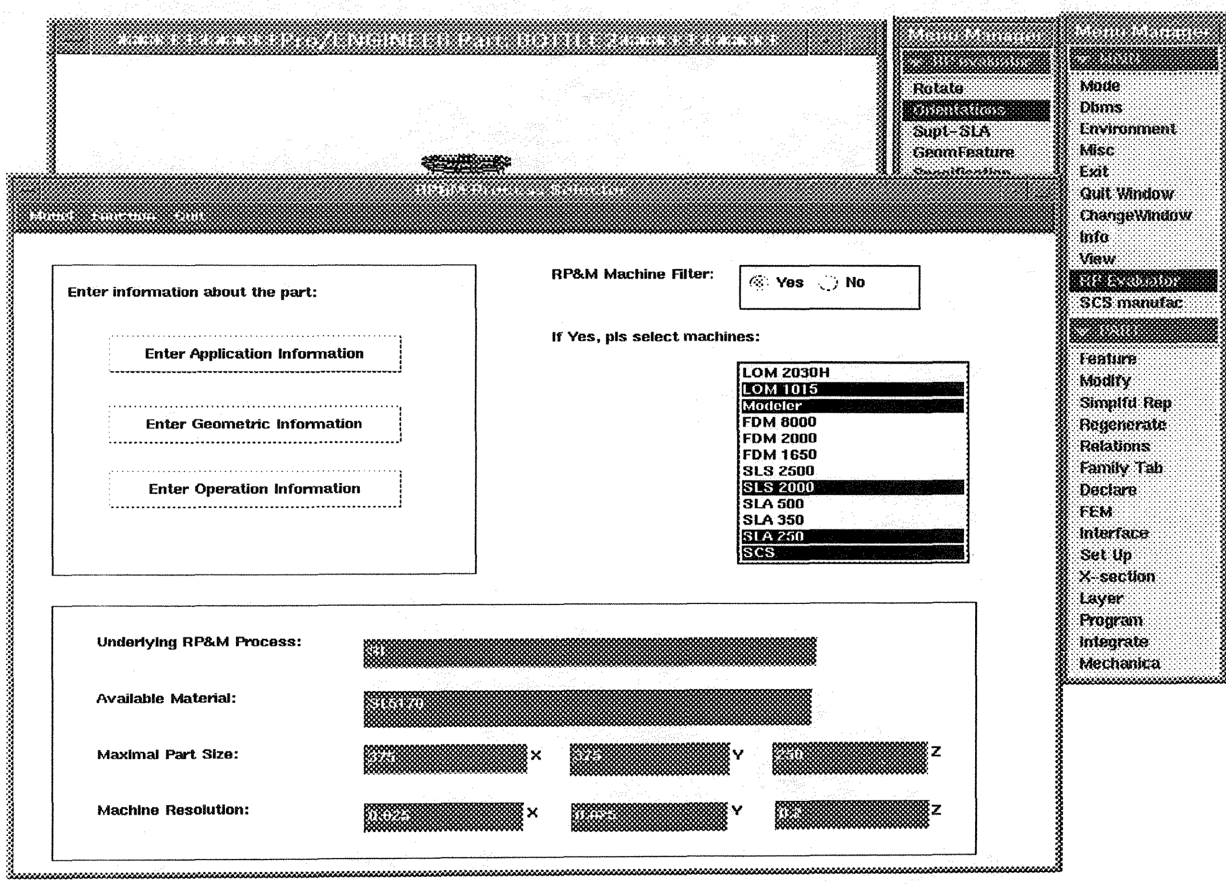


Figure 6 Implementation of the Knowledge-based RP&M Material/Machine Selector

A perfume bottle, shown in Figure 7-(1), is used as a visualisation application case. In order to evaluate the visual appeal of this design, the designer want to build a physical model to show to potential customers for their comments. A number of RP&M machines, namely SLA 250, JSC-2000, SLS 2000, LOM 1013H and Concept Modeler, are assumed to be available to the designer. Since the prototype is used for visualisation purpose, the designer's requirement on dimensional tolerance is not critical. The surface finish of the prototype, however, should not be too coarse and affect the judgement of customers. Based on the designer's requirements, the application-related inputs are set as the following:

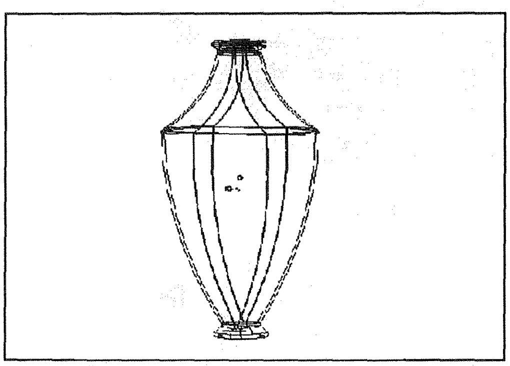
Application Category: *Visualisation Model*
Application Purpose: *Concept Proof*
Material Type: *No Preference*
Minimum Flexural Strength (N/mm^2): *30*
Minimum Flexural Modulus (N/mm): *600*
Minimum Tensile Strength (N/mm^2): *30*
Minimum Tensile Modulus (N/mm): *600*
Minimum Material Hardness (Shore D): *30*
Resistance to Humidity: *Normal*
Resistance to Heat: *Normal*

The descriptions on the general shape of the product model are set as:

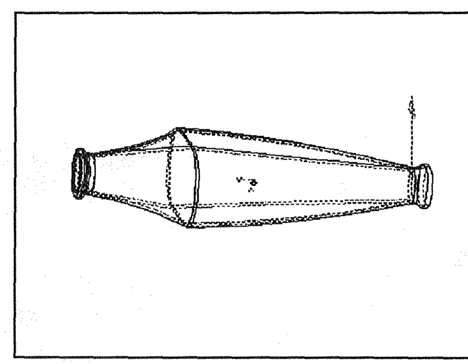
Thin Wall: *None*
Cavities with small opening: *Yes*
Deep Holes (L/D>5): *None*
Fine Features: *None*
Sculptured Surfaces: *Some*
Size of the Part: *Medium*
Ratio of Volume vs. Size: *Small*

The operational factors are set as following:

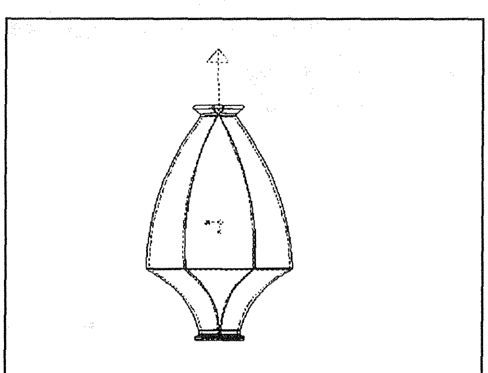
Dimension Tolerance: 0.1mm~0.3mm
Surface finishing: $16<R_a<266$ micro
Time factor: Normal
Cost factor: Normal



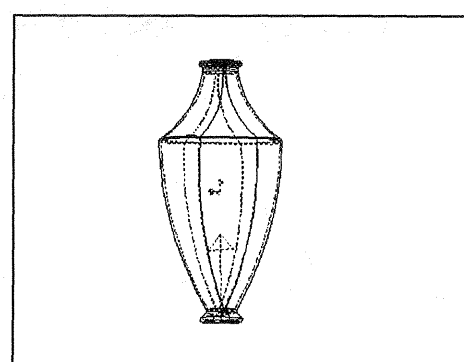
(1) Concept Design of a Perfume Bottle



(2) Orientation with the least building height



(3) Orientation with the Least Staircase Effect



(4) Orientation with the least overhang

Figure 7 Perfume Bottle in Different Orientations

Geometric attributes of the product model in different orientations, as shown in Figure 7, are evaluated in the environment of a CAD system and stored in a flat file. The flat file is then passed to the knowledge-based module for examination. For this application case, all RP&M material included in the material database are found to be suitable. The suitable machines however do not include LOM. The large internal cavity in the model prevents it from using the LOM process. For the suitable combination of RP&M material, machine and orientations, the manufacturing time and cost are computed. According to the user's considerations on time and cost, the optimal solution is selected, i.e. the combination of P400ABS (material), Concept Modeler (an FDM machine), and the orientation shown in Figure 7-(4). Should the user change the requirements, the selection would be restarted.

6 Conclusion

An object-oriented approach for knowledge-based decision-support in RP&M part fabrication has been introduced in this paper. Based on the approach, an RP&M material/machine selector has been developed to assist the user select the right RP&M material/machine for a specific part fabrication. Using rule-based reasoning and database, the selector first finds the applicable RP&M material/machines. From the list of applicable RP&M systems, the optimal combination of material, machine and part orientation is then found out based on the minimisation of cost.

At present, information about the four RP&M processes, namely SL, SLS, FDM and LOM, are included in the RP&M material/machine database. While the developed software focus on the selection of material and machine in RP&M part fabrication, the object-oriented knowledge-based approach can be extended to handle other tasks arising in the integration of design and prototyping/manufacturing activities. With the compilation of more comprehensive machine databases, the decision-support system is expected to provide a detailed process plan for the fabrication of a specific application with RP&M.

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