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# Preliminary design and manufacturing planning integration using web-based intelligent agents

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Software agents have been increasingly used in the product and process development in industry over the past years due to the rapid evolvement of the Internet technology. This paper describes agents for the integration of conceptual design and process planning. Agents provide mechanisms to interact with each other. This mechanism is important since both of those processes involve negotiations for optimization. A set of design and planning software agents has been developed. These agents are used in a computer-based collaborative environment, called a multi-agent platform. The main purpose of developing such a platform is to support product preliminary design, optimize product form and structure, and reduce the manufacturing cost in the early design stage. The agents on the platform have access to a knowledge base that contains design and planning rules. These rules are derived from an analysis of design factors that influence process and resource planning, such as product material, form, shape complexity, features, dimension, tolerance, surface condition, production volume, and production rate. These rules are used by process planning agents to provide process planners with information regarding selecting preliminary manufacturing processes, determining manufacturing resources, and constructing feedback information to product designers. Additionally, the agents communicate with WEB servers, and they are accessible by users through Internet browsers. During performing design and planning tasks, agents access the data pertinent to design and manufacturing processes by the programming interfaces of existing computer-aided design (CAD) and manufacturing system. The agents are supported by a developed prototype agent platform. The agents and the platform enable the information exchange among agents, based on a previously developed integrated design and manufacturing process object model.

*Keywords*: Conceptual design, intelligent agents, manufacturing agents, process planning, systems integration.

## 1. Introduction

Current Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems are usually operated in a stand-alone mode. To increase the current capability of these systems, it is necessary to include other software systems, tools, existing databases, or knowledge bases into the current CAD/CAM systems. It is estimated that the choices made by the product designer in the preliminary design stage affect 60% of all product life cycle costs (Welch and Dixon 1991). The choices include product function, behavior, form, structural complexity, and materials. The impact of preliminary design choices on manufacturing process and cost is usually significant.

Some fundamental problems that cause the difficulty in integrating preliminary design and manufacturing planning include:

(1) Interoperability among heterogeneous software systems and tools is generally not available. The conceptual design and process planning software systems are not interoperable across software ownership boundaries.
(2) Computing environments are usually distributed. Preliminary design systems and process planning systems are usually not co-located.
(3) Web-based collaboration between the process planning activity and the preliminary design activity is currently not available. This impedes collaborative activities in a distributed computing environment within a company's engineering department.

Considerable efforts (Venkatachalam *et al.*, 1993; Feng and Thang, 1999; Feng *et al.*, 1999; Feng and Song, 2000 a,b) have been made to provide information models that integrate process planning with preliminary design information. One critical element in the integration effort is a knowledge base that has rules mapping design specifications to processes and equipment for manufacturing various types of parts. These rules are stored in a knowledge base, which is used by intelligent agents that are executed on an agent platform. These agents are connected to a computer network, and they interact with users via web browsers. Users view the status of jobs being processed and messages passed from one agent to another. Agents assist designers and process planners to optimize the design and Process plan accessing the predefined design and planning rules.

An enabling technology for flexible integration is a multi-agent system (Shen et al., 2001; Wooldridge, 2002). This technology provides software developers with methods and tools to link agents with various engineering software tools together. Using computer network sockets or Common Object Request Broker Architecture (CORBA) (http://WWW.omg.org), agents can communicate with engineering application software systems, such as CAD/CAM systems, mathematical solving tools, expert systems, and database management systems. The intelligence of agents can be either embedded in the code or stored in the knowledge base. Agent knowledge includes the logic for achieving the goals of the agent and specific problem solving capability. Additionally, agents can be connected to web services (Shen *et al.*, 2002). Users can, therefore, interact with the agents remotely using Internet. Using agents with socket or CORBA, software developers can integrate software tools, systems, knowledge bases, and databases into a readily available suite of services that can provide product designers and manufacturing engineers with many new capabilities, such as integrated preliminary design and process planning.

Many research efforts have addressed ways of using agents in integration of detailed design, detailed Process planning, manufacturing control, and execution in the product development process, as described in Section 2. These research efforts are based on non-standard interfaces and communication protocols. Standards for autonomous agents and multi-agent systems have been emerging rapidly (http://www.fipa.org; DAML, http://www.daml.org). Agents can use the Agent Communication Language (ACL) (http://www.fipa.org) and other emerging languages, such as DAML+OIL (http://www.daml.org), Web Ontology Language (http://www.w3.org/TR/owl-guide), and commitment-based ACL (Fornara and Colombetti, 2003), to communicate with each other on an agent platform. The ACL is being developed as an international standard. DAML, another agent communication language, is XML-like and still being developed. Also, the important issue of the use of intelligent agents in assisting preliminary design and the integration of it with other engineering activities in the product development process was rarely addressed. This paper presents a multi-agent platform that is based on international standards and demonstrates the integration of the preliminary design activity and the process planning activity for the purpose of optimizing manufacturing costs and time in the early design stage.

Some specific new ideas that are explored are as follows:

(1) Proposed and demonstrated mechanisms using software agents for software components to communicate with each

other across computer networks with as few changes as possible to the original software.
(2) Processes (software behavior) can be changed, and services can be added without changing existing codes.
(3) Software capabilities are defined and registered in a database where others can access.
(4) Representation of the domain knowledge and objects shared by different software systems is open and well defined.
(5) web-accessibility are built into agents so that they can be remotely controlled and monitored. Software agents enable collaborative work in process planning with design.

This paper describes a design and implementation of a multi-agent platform prototype concurrent preliminary design and process planning. Section 2 reviews the state of the art in design information modeling and process planning methods and technologies. Section 3 presents the agent platform that supports multi-agent communication. Section 4 describes an analysis of factors in design and planning rules that are used in the manufacturing process planning activity. A description of a process planning knowledge base is also included in this section. Section 5 discusses a case study. Section 6 summarizes the process planning knowledge analysis and platform design and points out the future work.

## 2. The state of the art in design and process planning research and technology

Product information model is the basis for sharing and exchanging the information about a design. Roseman describes a design object in terms of structure, behavior or function. Modeling multiple views of design objects is presented for a collaborative CAD environment (Rosenman and Gero, 1996). Gorti *et al.* present an object-oriented representation for product and design processes. This model forms the basis for design knowledge representation (Gorti *et al.*, 1998). Gero describes a design prototype as a conceptual schema for presenting a class of a generalized heterogeneous grouping of elements derived from a similar design case. A designed artifact can be broadly interpreted in terms of the three variable groups of function, behavior, and structure (Gero, 1990). A CAD system, MAPS-1, for suggesting candidate manufacturing process and material combinations for part has been developed. It takes batch size, bulk shape, part shape, tolerance, surface roughness, etc. into account to select manufacturing processes and materials (Dargie *et al.*, 1982). The system can select materials and primary processes based on the geometry and shape of components. Another computer-added manufacturing process selection system has also been developed. This system demonstrates the net-shape process planning capability for several forming processes, such as injection molding, die casting, powder metallurgy, hot extrusion, investment casting, and forging (Yu *et al.*, 1993). An expert system for selection of casting process has been introduced. The system generates cast process plans based on material, tolerance, mass, thickness, surface roughness and economic volume, not focusing on shape (Darwish and El-tamimi, 1996). Computer Oriented materials, processes, and apparatus selection system (COMPASS) has been developed as a meta planner that is to help designers to identify potential manufacturing problems in the early design process. The meta planner can be integrated into CAD/CAPP/CAM system. It generates a high-level process plan that contains complete coverage of all feasible processes for the design (Chan *et al.*, 1998), Cecil and Rodriguez have proposed a distributed framework for product development using CORBA (Cecil and Rodriguez, 2003). Using this framework, the development of a distributed process planning environment has been completed. The process planning modules are located in Las Cruces (New Moxieo), Monterrey (Mexico), and State College (Pennsylvania). Also, they developed managing software to facilitate the communication among different application software tools. Currently, users can use the implemented system to obtain real-time process planning solutions based on availability of machines and tools. This environment is used primarily for teaching Internet-based manufacturing concepts to students. Lee and Kims have developed a CORBA-based distributed feature modeling system for design (Lee et al., 2001). The system was developed on a client-server architecture. A feature data model was also specified in their work that is consistent with the product data model in ISO 10303, commonly known as

STEP. The design feature can be used for process planning. For electronic product design, Konduri and Chandrakasan have developed a framework for web-based design of VLSI systems (Kondori and Chandrakasan 1999). This framework provides interfaces to CAD/CAM systems such that a distributed and collaborative design environment can be achieved. Sun, Zhang, and Nee have developed a multi-agent system for concurrent product design and process planning at the detailed level (Sun *et al.*, 2000). The approach enables geographically distributed project staff to work collaboratively using agents. The system also provides a means to integration heterogeneous software tools into a web-accessible system.

Process planning is an important link in the manufacturing cycle. Computer-Aided Process Planning (CAPP) systems bridge CAD and CAM. The process planning activity is to define in detail, the manufacturing process that transforms raw materials into the product according to designer specification. Traditional process planning depending only on human experience and skills has many drawbacks: it is highly-labor intensive, time consuming, subjective, limited in variety, and inconsistent in quality. With the advancement of computer technology, CAPP has the advantage of reducing the cycle time for process planning, but have limited capability in terms of improving manufacturability (Korde *et al.*, 1992). The past research efforts on CAPP research are mainly on detailed process planning in metal removal, or machining processes (ElMaraghy 1993; Eversheim and Schneewind 1993). One type of process planning is the case-based CAPP, which has been focused on retrieving past experience from the process plan repository, modifying the old process plan for new parts. The new plan is then stored in the repository for future references (Yang *et al.*, 1994). Another type of process planning is feature-based CAPP, which has been focused on generating process plans of features at the beginning. Then, it generates the manufacturing operation sequences of part, based on manufacturing knowledge (Kang and Nnaji). To generate the complete manufacturing process for a product, these process planning technologies utilize detailed design data, such as detailed geometry, topology, dimensions and tolerances, material, and surface conditions. Wright *et al.* have developed Cybercut (Wright and Dornfield, 1998). It is an Internet-based design and machining process planning system. It is web-accessible and has many functional modules, such as the geometric modeling module, machining feature recognition module, and machining task planning module. Huang and Mak proposed an approach that utilizes the Internet in design for manufacturing and assembly analysis (Huang and Mak 1999). They have implemented a web-based assembly advisor to allow remote access to the assembly analysis rules. Heikkila, Kollingbaum, and Bluemink proposed an agent architecture for manufacturing control (Heikkila *et al.*, 2001). A list of requirements and a component architecture have been specified. Agent communication protocols and agent system structure are described in the paper. KQML (Wooldridge and Jennings 1995) is used as the communication language that agents use for sending information on process plans and manufacturing schedule.

Most existing CAPP systems have the capability of operation planning without considering manufacturing time and cost of a conceptual design. Time and cost estimation is necessary for design optimization. Additionally, the WEB technology makes it possible to share, manage and exchange product information among various engineering applications over the Internet (Tian *et al.*, 2002), Design and planning systems cannot be dynamically integrated into a suite of functionalities using the Internet technology to suite engineers' constantly changing needs. The future CAD/CAPP/CAM integration should be web-based and accessible by intelligent agents.

## 3. Multiple intelligent agents for design and planning integration

A prototype agent platform has been developed at the National Institute of Standards and Technology (NIST). It provides agents with communication mechanisms for exchanging messages and sharing commonly used data. Figure 1 shows groups of agents connected to the platform, supporting design and process planning integration. The agent platform, supported by JADE (http://www.cselt.it), is basically a communication

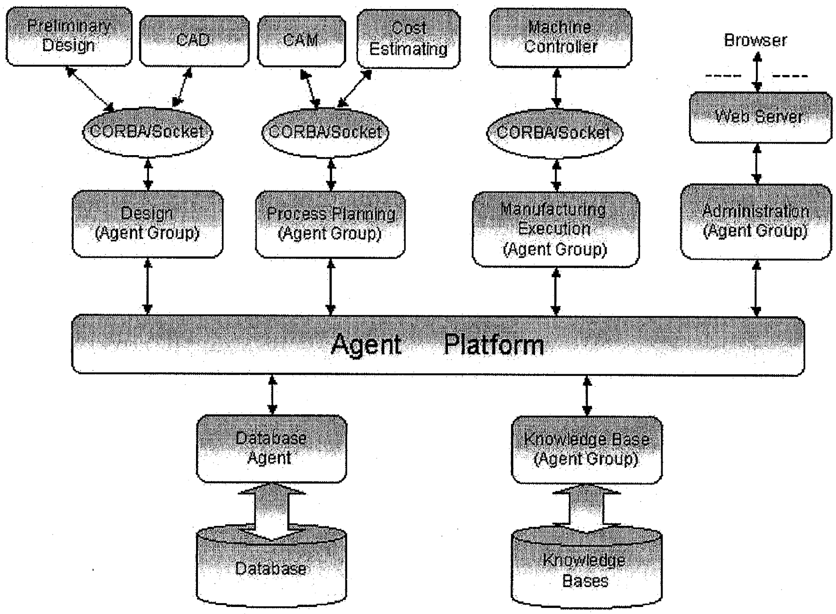


**Fig. 1.** Multi-agent platform prototype.

mechanism through which design software systems, process planning software systems, databases, and knowledge bases can be integrated.

The design agent group consists of preliminary design and detailed design agents. The preliminary design agent performs functional, behavioral, and embodiment design. The detailed design agent performs geometric modeling of parts and product assembly, tolerance assignment, and drawing. This agent uses a CAD system to perform these functions by communicating via CORBA and the programming interface to the CAD system. Note that CORBA can be replaced by Transmission Control Protocol/Internet Protocol (TCP/IP) (Comer, 1995) sockets with some changes to agent software if CORBA tools are not available.

The process planning agent group consists of agents that provide the functions of preliminary process planning, detailed process planning, and cost estimating. The preliminary process planning agent performs process selection, resource selection, and process sequencing. The detailed process planning agent has an embedded CAM system that provides the agent with the capability of tool path planning and numerical control (NC) program generation. Cost estimating agent has mathematical formulae to estimate the costs of materials, tools, machine usage, labor, setup, etc.

The administration agent group consists of a web agent and an Extensible Markup Language (XML) agent. The web agent allows users to interact with agents using a web browsers. For example, a user can start, stop, and check the status of an agent. The user can also select another Set of logic to change the behavior of the agent. The XML agent provides users with access to information in the databases, displayed in a human-readable form via Internet. This will allow some operators and the administrator to update the knowledge base and database.

In addition to engineering and administrative agent groups, there we two other types of agents on the platform. The database agent interacts with a relational database to provide other agents with requested data, such as part design information, material, process plan, NC program, machine, tool, and fixture information. The knowledge base agent group is consisted of both a knowledge base handling agent and a mathematical tool handling agent. The former interacts with a rule base that stores design and planning rules. The planning rules will be discussed in Section 4. The latter interacts with a mathematical software system that solves differential equations, such as machine tool chatter for determining optimal cutting parameters, tool life estimating, manufacturing cost estimaing, and manufacturing time estimating.

## 4. Preliminary process planning knowledge for intelligent agents

Preliminary process Planning is a manufacturability assessment process conducted in the early product design stage. It is an activity to determine primary manufacturing processes, select resources and equipment, and estimate manufacturing costs. It supports product design to optimize product form, configuration, and material selection and to minimize the manufacturing costs. This activity primarily evaluates the manufacturability of a preliminary design. Figure 2 shows the functions of preliminary process planning. The input parameters include product material, form, shape complexity, dimensions, tolerances, surface conditions, production quantity, and production rate. The process planning activity is controlled by manufacturing resource/process selection rules constrained by manufacturing process capabilities. To perform this activity, a process planner usually uses a computer-aided process planning system. The results are candidate manufacturing processes and selected resources with estimated manufacturing time and cost.

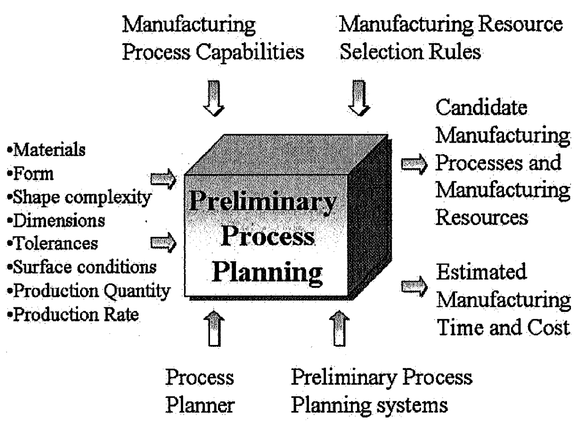


**Fig. 2.** Preliminary process planning.

### 4.1. *An architecture of a preliminary process planning system*

Figure 3 shows the architecture of integrated knowledge-based preliminary process planning functional components. It consists of an inference engine, a manufacturing knowledge base, a manufacturing resource database, and an artifact database. The manufacturing knowledge base contains process planning rules, and the manufacturing resource database stores descriptions of tools, machines, labor skills, and computer software capabilities. The inference engine is used to select candidate manufacturing processes and resources, and estimate the manufacturing cost/time based on manufacturing knowledge according to the design information. The design information is generated by a preliminary design system, which is integrated with a design knowledge base. Both the design information and manufacturing process information are integrated in this preliminary process planning system. The artifact database stores product information pertinent to preliminary process planning, described as the input parameters in Fig. 2. The semantic structures for information exchange between agents of design and process planning is based on an integrated design and manufacturing object model, as described in Feng and Song (2000 a,b). Preliminary process planning agents are in the process planning agent groups in Fig. 1. Their activities are coordinated by a process planning agent. The artifact database and the manufacturing resource database, shown in Fig. 3, are controlled by the database agent in Fig. 1. The manufacturing knowledge base in Fig. 3. is used by the knowledge base agent group to provide intelligence for agents in the process planning group. The preliminary design system is used by, the preliminary design agent.

### 4.2. *Knowledge-based preliminary process planning*

A critical functional component in the architecture is the preliminary process planning knowledge. This section discusses the design factors that are used by the system to select processes and resources to produce parts. The terms and objects used in this section are described in Feng and Song (2000 a). An associated object-oriented

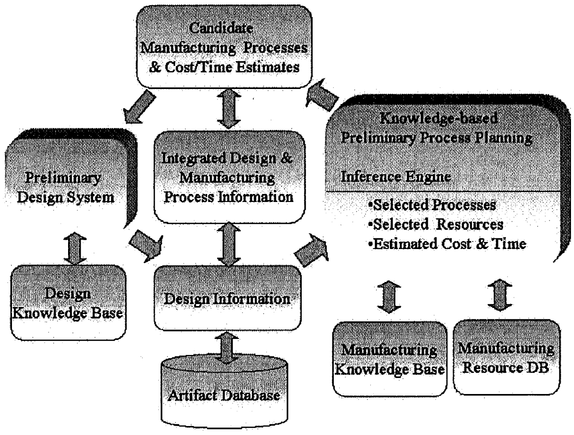


**Fig. 3.** The architecture of knowledge-based preliminary process planning functional components.

information model on manufacturing processes and resources is also presented in Feng and Song (2000 a). In the model, manufacturing processes are classified into part making, assembly, and inspection based on the characteristics of a process. This paper focuses on the part making processes.

#### 4.2.1. *Factors in preliminary process planning*

It is important to produce parts satisfying all the functional requirements at the minimum cost. In order to achieve this, an approach known as knowledge-based, integrated design and manufacturing planning is proposed. In this approach, the process plan with cost estimation can be performed and optimized as soon as a preliminary design is completed. The design knowledge used in this approach involves many preliminary design factors that influence the selection of preliminary manufacturing processes and resources. They are described as follows.

- **Shape and complexity**
  Manufacturing processes vary in their abilities to produce complex shapes. Each shape can be made by a number of different manufacturing processes, and each process can make a number of shapes. According to the basic shape characteristics of mechanical products, shape can be classified in ten categories: round, spherp, cone, wire, ring, bar, tube, flat, structured shape, and frame. Shape complexity can be divided into eight subclasses: uniform cross section, change at end, change at center, spatial curvature, closed one end, closed both ends, transverse, and irregular. Figure 4 shows this classification with examples. Each shape and shape complexity can be generated by means of many manufacturing processes. The main shape and shape complexity classification are used to select preliminary manufacturing processes to generate the shape of products. This classification is derived on the classification developed previously by Kalpakjian (2000). Figure 5 shows the classification of machining features. The forms of these features can be classified into cylinder, plane, chamfer, conic surface, free-form surface, hole, step, pocket, slot, thread, and gear-teeth. This machining feature classification is used to select machining processes to generate the shape of products (Kalpakjian, 2000).

- **Material**
  The selection of suitable materials in a product design is a key decision for manufacturability, and it can lead to satisfactory product with low manufacturing cost. Material selection should meet the function and cost requirements. The functional requirements depend mainly on the physical and mechanical properties of materials. The material properties directly influence the production methods. The selection of a material must be closely coupled with the selection of a manufacturing process. The goal is to select the material and process that maximize quality and minimize the cost of the part. Special manufacturing processes are typically limited to certain types of material. Some types of material are limited to particular manufacturing processes. For example, plastics can be molded, but cannot be forged; however, steels can be cast or forged, but cannot be vacuum formed. In general, the selection of material determines a set of processes that can be used to manufacture parts.

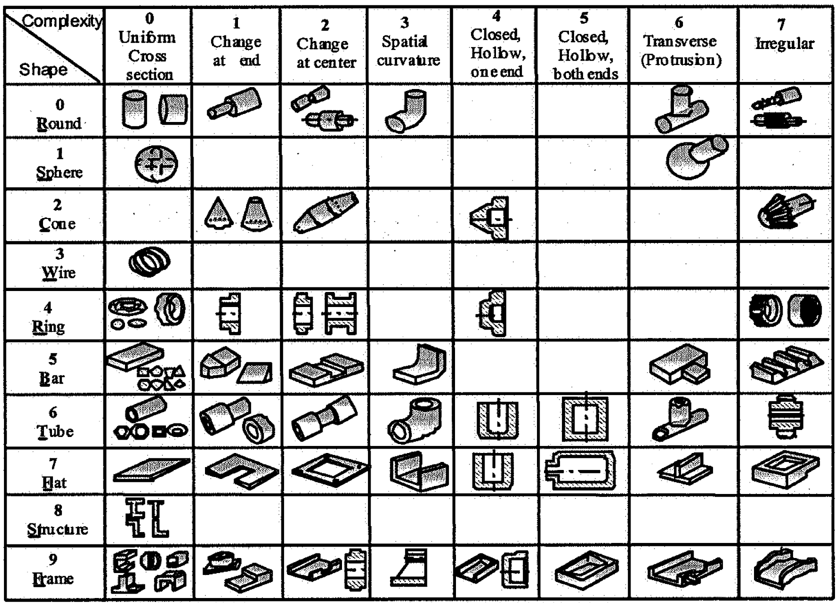


**Fig. 4.** A classification of shape and complexity.

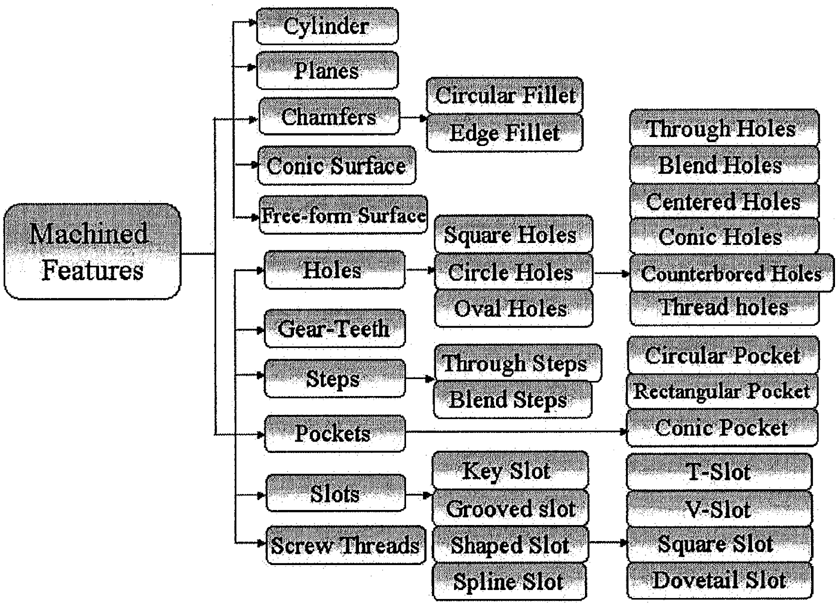


**Fig. 5.** A classification of machined features.

- **Size, weight, production quantity, and rate**
  The product size is a critical factor in selecting the processes. Generally, the maximum size that can be produced by a given process or technique is most often limited by the size of available equipment. In some processes, however, there are limitations due to process conditions, such as a sand-casting mold that can not stand up to the long solidification times imposed by a very heavy wall thickness. Moreover, some processing techniques are limited in their capacity to produce small sizes, especially thin walls. The wall thickness of a casting may be limited by the fluidity

of metal, and the thickness of a forged part is limited by die pressures generated when the diameter-to-thickness ratio becomes large. Therefore, very thin, very small, or very large components usually can only be made under special circumstances and with extra costs. The weight of a product, similar to the size factor, also limits the selection of manufacturing processes. For example, components weighing more than 50 kg are usually difficult to produce using die casting. Other significant factors in manufacturing cost are the product quantity and rate. They depend on the type of product. Usually, it is easier to increase production quantity and rate without increasing too much of the cost if the product shape simpler and less complex. The production quantity and rate are significant in process and equipment selection. Casting and molding are suitable for large volume production. They also influence the process parameter selection, such as increasing cutting speed and depth of cut in the machining processes to increase the production rate.

- **Tolerance and surface finish**
  In Tolerances and surface finish are important aspects in both design and process planning. In most cases, the tighter the tolerance requirements are, the higher the cost of manufacturing will be. Sand casting can produce loosely toleranced parts. For tightly toleranced parts, machining processes are usually selected. For tighter tolerance, electric discharged machining processes are selected. The smaller the surface finish is, the longer manufacturing time Will take with increased cost. Grinding reduces surface roughness of machined parts. With smaller surface roughness, lapping and hand polishing are selected with increased costs. Unnecessarily tight tolerance or surface finish specification are major couses of excessive manufacturing cost. Each manufacturing process is capable of producing a part to a certain surface finish and tolerance range without extra expenditures. The range of tolerances and surface finishes of manufacturing processes is an important criterion when manufacturing processes are being selected. Generally, each surface of a part should be made with as coarse a surface finish and as wide a tolerance as functionally and aesthetically acceptable.

### 4.2.2. *Manufacturing process knowledge and production-rule representation*

Many manufacturing process capabilities and process planning rules are available from literature and interviews with manufacturing engineers. Manufacturing process knowledge has to be put into knowledge bases to be useful. It may be represented in a number of ways, such as production-rule, semantic network, object, and frame. One popular method of knowledge representation is in the form of production-rule, which has the form "If-Then". Production-rules appear to be a natural way of modeling how humans solve problems, so the rules are typically human-interpretable. The manufacturing process rules are classified into two groups: forming process selection and material removing process selection. Other rules include resource selection, and cost estimation. These rules are stored in a knowledge base connected to the agent platform, as shown in Fig. 1. For example, the following is a production-rule to generate a sand casting process.

**Production-rule:**

```
Rule # 10;
If{
  (
    (mainShape.equals("Round"))&&
      (
      shapeComplexity.equals
        ("UniformCrossSection")||
      shapeComplexity.equals("ChangeAtEnd")||
      shapeComplexity.equals("ChangeAtCenter")||
      shapeComplexity.equals("SpatialCurvature")||
      shapeComplexity.equals("Protrusion")||
      shapeComplexity.equals("IrregularShape")
    )
  )||
  … …
```

```
(mainShape.equals("Frame")&&
  (
    shapeComplexity.equals("UniformCrossSection")||
    shapeComplexity.equals("ChangeAtEnd")||
    shapeComplexity.equals("ChangeAtCenter")||
    shapeComplexity.equals("SpatialCurvature")||
    shapeComplexity.equals("ClosedOneEnd")||
    shapeComplexity.equals("ClosedBothEnd")||
    shapeComplexity.equals("Protrusion")||
    shapeComplexity.equals("IrregularShape")||
  )
)&&
        (material.equals("AllMaterial")||
          material.equals("Castliron")||
          ......
          material.equals("Polymers")
      )&&
        (shapeSymmetry.equals("true")||
          shapeSymmetry.equols("false"))&&
        (shappAxisOfRotation.equals("true")
          ||shapeAxisOfRotation.equals("false")
      )&&
      (secondaryPositiveFeature.equals
                          ("Bosses")||
      ......
        secondaryPositiveFeature.equals
                    ("BlocksDrafts")
        )&&
        (Double.valueOf(maximumDimension).
              doubleValue() <= 10000.0)&&
        (Double.valueOf(sectionThickness).
              doubleValue() >= 3.0)&&
        (Double.valueOf(weight).
              doubleValue() <= 300000.0)&&
        (Double.valueOf(minimumTolerance).
              doubleValue() >= 1.5)&&
        (Double.valueOf(surfaceRoughness).
              doubleValue() <= 25.0)&&
        (Double.valueOf(surfaceRoughness).
              doubleValue() >= 12.5)&&
        (Double.valueOf(productionVolume).
              doubleValue() >= 1.0)&&
        (Double.valueOf(productionVolume).
              doubleValue() <= 100.0)
    }
Then
{
    processDescripti = "SandCasting";
    processSelect = 1;
    machiningProcessDecision();
}
Else
{
    processDescription = process
              Description;
    processSelectio = 0;
}
```

An inference engine, as depicted in Fig. 3, is a reasoning mechanism that processes the planning rules. Forward chaining is applied in this system to reason from facts or conditions to conclusions. The purpose of the inference engine is to select preliminary processes, manufacturing resources, and estimate manufacturing cost/time based on manufacturing knowledge according the design data. The inferencing process maps design and process capability information to a combination of manufacturing processes and resources.

## 5. Case study

Planetary gearboxes are widely used in automotive and aerospace industries. A preliminary design of the output housing component of a planetary gearbox is used as an example to test the implementation of the knowledge base and agent communications. Figure 6 shows a 3-D solid model representation of the output housing. The part model is generated using Pro/Engineer™ Version 2001 (Please see Disclaimer following Section 6). Design data such as geometry, tolerance, surface roughness, and material are retrieved from the CAD system using the Pro/Toolkit™ software with programs implemented in the C programming language. The data are transferred agents, programmed in

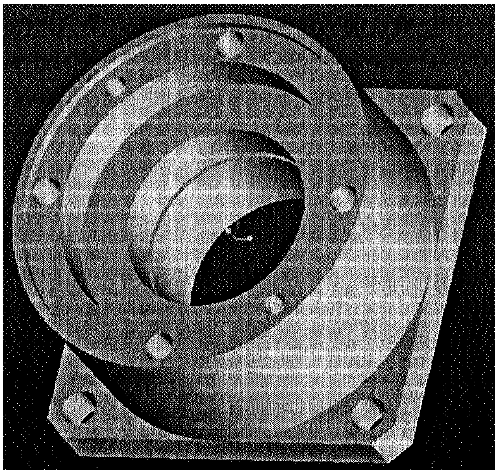

**Fig. 6.** Solid model of the output housing.

the Java$^{TM}$ programming language via computer network sockets in TCP/IP. The agent platform is described in Fig. 1. Agents communicate with the CAD/CAM system using the vendor-provided C programming interface and TCP/IP sockets.

Based on the manufacturing rule in the developed knowledge base, the process planing agent generates preliminary manufacturing processes. It then selects manufacturing resources, such as machine tools and cutting tools. Finally, it optimizes the selected preliminary manufacturing processes using a mathematical model of the machining process.

Figure 7 shows a graphical user interface for the artifact information database with a web browser. The information is used as the input to the search in the knowledge base for selecting appropriate processes. The artifact name is Output Housing, which is for protecting the sun, planetary, and ring gears. The main shape is a type of frame. The complexity of the shape is a uniform shape, but it has a change of size at one end. It is true that the shape is symmetric, in this case, about an axis. It is also true that the shape is rotational. Major secondary positive features are blocks. Secondary negative features include cylindrical surfaces, large through holes, small through holes, large blind holes, and counter bored holes. The workpiece material is cast iron. The part is within an envelope of 60 mm cube. The minimum cross sectional thickness is 10 mm. The weight limit is 20 g. The tightest tolerance in the part is 0.5 mm. The surface roughness requirement is 6.4 $\mu$m (Root Mean Squared). The implemented Java code transmit the data from the web browser to an expert system, implemented using Jess (http://herzberg.ca.sandia.gov/jess). Manufacturing process and resource selection rules are stored in Jess. The design and process data are stored in a database implemented in an Oracle$^{TM}$ database management system. The Java database connector software is used to facilitate the queries of agents to the database. The mathematical equations for estimating manufacturing cost and time are implemented in MatLab$^{TM}$. The MatLab-C programming language interface and socket are used to facilitate the communication between agents and cost/time estimating functions in MatLab scripts. When the user selects the Run button, relevant rules will be triggered. The results including the candidate manufacturing processes and resources are shown in Fig.8.

The candidate manufacturing processes are selected for manufacturing the output housing. The first set includes shell casting, turning, drilling, counterboring, and tapping. The associated equipment includes machine tools, fixturing tools, and cutting tools. Machine tools include a shell-casting machine, lathe, and computerized numerically controlled machining center. Fixturing tools include a flask, chuck, and vises. The cutting tools include turning cutters, drills, milling cutters, boring tools, and tapping tools. The second set of processes includes permanent casting, turning, and drilling. The associated equipment for this set of processes includes a permanent-casting machine, lathe, and computer numerically controlled machining center, fixtures, and tools.

Figure 8 shows that the optimal preliminary manufacturing process for the output housing component with respect to cost is the set of shell casting, turning, drilling, counterboring, and tapping processes. As the name suggests, this process includes three manufacturing activities: casting, turning, and drilling. The casting activity includes setup, handling, shell casting, loading and unloading. The turning activity includes setup, handling, loading, unloading, cylindrical turning, the large through hole boring, and the large blind hole boring. The drilling activity includes setup, handling, load/unload, small through hole drilling,

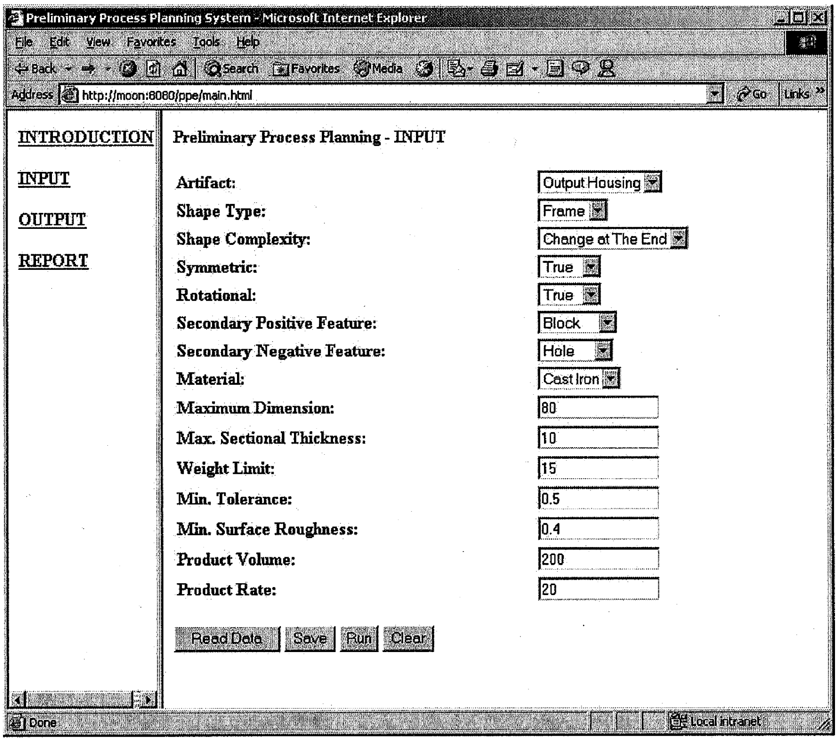


**Fig. 7.** Artifact information from database.

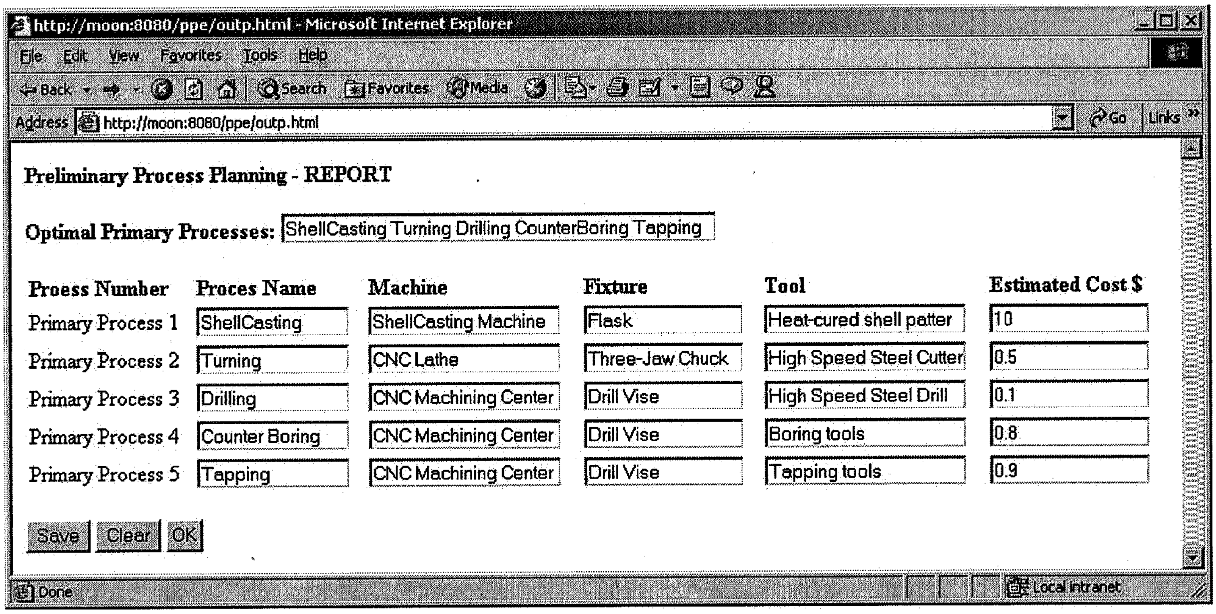


**Fig. 8.** Optimal primary process and resources.

and counter hole boring. The selected set of the processes is the least costly combination of manufacturing activities that can produce the part. The software also evaluated several other combinations of activities, such as (milling, turning, drilling) and (die casting, turning, milling) (Feng and Song, 2000a).

## 6. Conclusions and future work

Design factors, such as form, material, tolerance, surface condition, shape complexity, size, weight, and quantity, influence process planning a great deal. A knowledge base was developed to capture these factors and their mappings to possible manufacturing processes and resources. Process planning agents and a multi-agent system were designed and prototyped to utilize this knowledge, to aide designers to make more cost-effective decisions in the preliminary design stage, The agents use the knowledge for selecting manufacturing processes and resources. They communicate via an agent platform that provides for the integration of heterogeneous systems of CAD, CAM, CAPP, database, knowledge base, and mathematical-equations-solving software. The agents are also web-based. They are accessible by designers, process planners, and manufacturing engineers through web browsers. Because of the web accessibility, the system supports collaborative work in concurrent design and manufacturing. Additionally, the new software architecture in the paper enables knowledge and data to be transmitted between agents/systems using the Agent Communication Language.

Future work includes further development of the platform, including standard message content language and ontology. Many more agents need to be developed to perform more complicated design, process planning, and cost estimating tasks. Furthermore, the following tasks will be performed: (1) validate the prototype system using more industrial cases, (2) explore the interrelationships between the design factors to better sequence the selected processes and determine process parameters, and (3) develop a draft standard that specifies a framework for the interoperability of a set of software products used in the manufacturing domain and facilitate its integration into CAD and manufacturing systems. The system should also be extended to fully support collaborative work in concurrent design, manufacturing planning, and optimization.

## Disclaimer

No approval or endorsement of any commercial products by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper in order to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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