# Preliminary Design and Manufacturing Planning Integration Using Intelligent Agents


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**ABSTRACT:** Intelligent agents can enable the integration of preliminary design with manufacturing planning software systems. These agents execute in a computer-based collaborative environment called "multi-agent platform." A prototype agent platform supporting the integration of preliminary design and manufacturing planning has been developed at NIST. These agents have access to a knowledge base that is implemented by rules, generated by mapping design information to process and resource selections. The 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, and production volume. Process planning agents provide process planners with information regarding selecting preliminary manufacturing processes, determining manufacturing resources, and constructing feed-back information to product designers. The agent platform enables the information exchange among agents, based on the integrated object model. The main purposes of developing such a platform are to support product preliminary design, optimize product form and structure, and reduce the manufacturing cost in the early design process.


## 1. INTRODUCTION

Choices made during preliminary design determine product function, behavior, form, structural complexity, and materials. It is estimated that these choices affect 60% of all product life cycle costs [1]. Therefore, the impact of preliminary design choices on manufacturing process and cost is usually quite significant.

To reduce these costs, considerable efforts [2-6] 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. An enabling technology for flexible integration is multi-agent systems [7]. This technology provides software developers with methods and tools to link various engineering software tools together.

This paper describes a design and implementation of a multi-agent platform prototype for concurrent design and process planning activity integration. Section 2 presents the agent platform that supports multi-agent communication. Section 3 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 described in this section. Section 4 discusses a case study. Section 5 summarizes the process planning knowledge analysis and platform design and points out the future work.

## 2. MULTIPLE INTELLIGENT AGENTS FOR DESIGN AND PLANNING INTEGRATION

A prototype agent platform has been developed at 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 is basically a communication mechanism through which the design software, process planning software, database, and knowledge base can be integrated.

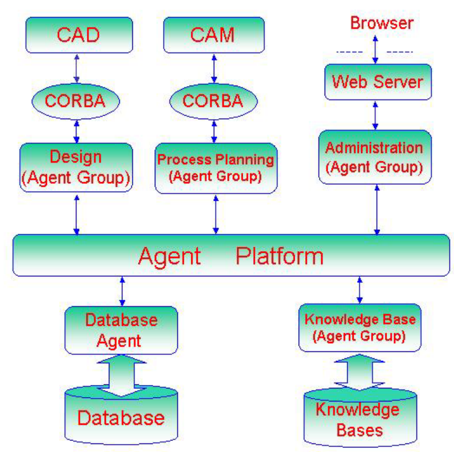


Figure 1 Multi-agent platform prototype

The design agent group consists of agents that can perform functional, embodiment, and detailed design. The detailed design agent uses a computer-aided design (CAD) system by communicating via its programming interface, with the Common Object Request Broker Architecture (CORBA) as the communication mechanism between the agent and the CAD system. The process planning agent group consists of agents that provide the functions of process selection, resource selection, and detailed process planning. The detailed process planning agent has an embedded computer-aided manufacturing (CAM) system that provides the agent with the capability of tool path planning and numerical control (NC) program generation. The administration agent group consists of a web agent and an Extensible Markup Language (XML) agent. The web agent allows users to interact with start and stop agents. The XML agent provides users with access to information in the databases, displayed in a human-readable form via web browsers.

In addition to engineering and administrative agent groups, there are 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, process plans, NC programs, and machine, tool, and fixture information. The knowledge base agent group has 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 3. The latter interacts with a mathematical software system that solves differential equations for machine tool chatter for determining optimal cutting parameters.

## 3. 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 that attempts 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, based on product material, main shape, shape complexity, dimensions, tolerances, surface conditions, and machining volume. The results are selected manufacturing processes and resources, with estimated manufacturing time and cost. Process planners usually perform the planning functions using a computer-aided process planning system.

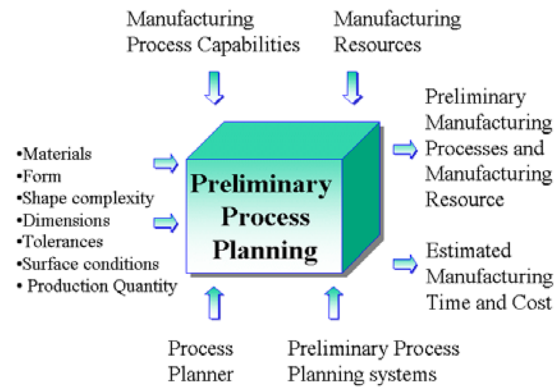


Figure 2 Preliminary process planning

### 3.1 Architecture of a Preliminary Process Planning System

Figure 3 shows an architecture of integrated knowledge-based preliminary process planning functional components. It consists of an inference engine, a product database, a manufacturing knowledge base, and a resource database. The inference engine is used to select preliminary manufacturing processes and resources, and estimate manufacturing cost/time based on manufacturing knowledge according to product information. The product database stores product information pertinent to preliminary process planning. The manufacturing knowledge base has process planning rules. The manufacturing resource database stores descriptions of tools, machines, labor skills, and computer software capabilities. The semantics for information exchange used by agents between design and process planning is based on an integrated design and manufacturing object model, described in [3,4].

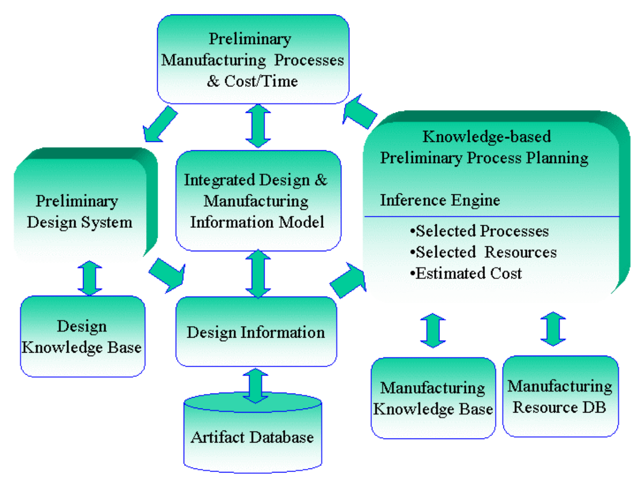


Figure 3 Architecture of knowledge-based preliminary process planning functional components

### 3.2 Knowledge-Based Preliminary Process Planning

This section discusses the design factors that are used by process planners to select processes and resources to produce parts. The terms and objects used in this section are described in [3]. An associated object-oriented information model on manufacturing processes and resources is also presented in [3]. 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.

#### 3.2.1 Factors in a preliminary process planning

It is important to produce parts satisfying all functional requirements at the minimum cost. To achieve this, an approach known as knowledge-based, integrated design and manufacturing planning can be performed. In this approach, process plan and 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.

- **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. Shape can be classified, according to basic shape characteristics of mechanical products, in ten categories: Round, Sphere, Cone, Wire, Ring, Bar, Tube, Flat, Structure 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. Our work is based on a classification developed previously by Kalpakjian [8].

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.

- **Material**

The selection of the suitable materials in a product design is a key decision for manufacturability, and it can lead to a satisfactory product with low manufacturing cost. Material selection should meet 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 certain manufacturing processes. For example, plastics can be molded, but cannot be forged; steels can be cast or forged, but cannot be vacuum formed. In general, the selection of the material determines a set of processes that can be used to manufacture parts.

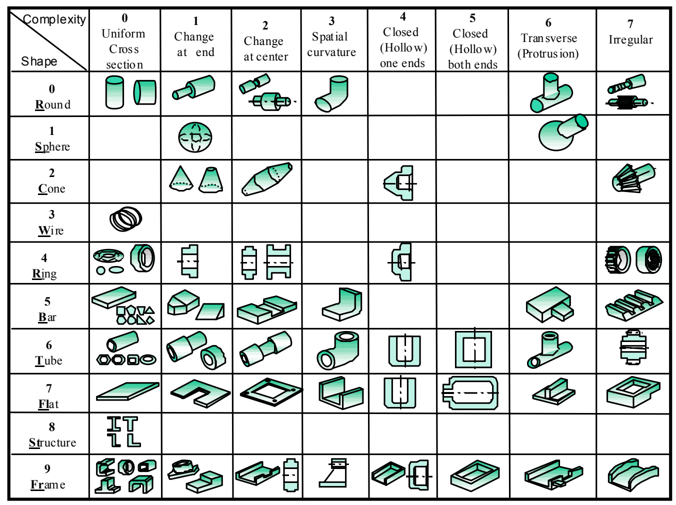


Figure 4 Classification of shape and complexity

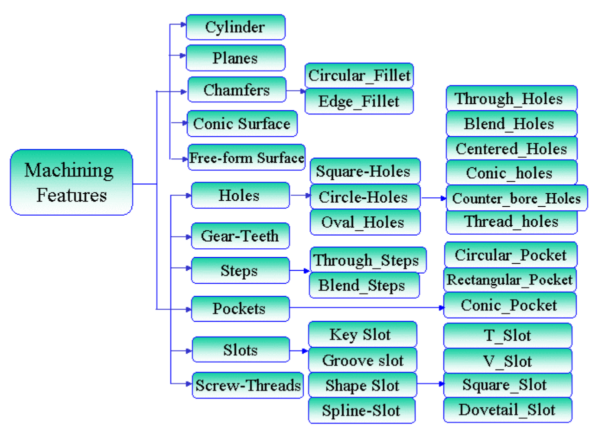


Figure 5 Classification of machining features

- **Size, weight, and production quantity**

Product size is a critical factor in selecting 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. Another significant factor in manufacturing cost is the product quantity. Production quantity depends on the type of product, and plays a significant role in process and equipment selection.

- **Tolerance and surface finish**

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 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 specifications are major causes 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.

### 3.2.2 Manufacturing process knowledge and production-rule representation

We have summarized many manufacturing processes and their capabilities according to previous research results [3]. Manufacturing process knowledge 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 production-rule, which has the form “If-Then”. Production-rules appear to be a natural way of modeling how humans solve problems, so 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 Figure 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("All Material") ||
         material.equals("Cast Iron") ||
         ……
         material.equals("Polymers")
       ) &&
       (shapeSymmetry.equals("true") ||
         shapeSymmetry.equals("false")) &&
       (shapeAxisOfRotation.equals("true")
        ||shapeAxisOfRotation.equals("false")
       ) &&
       (secondaryPositiveFeature.equals(" Bosses") ||
        ……
        secondaryPositiveFeature.equals(" Blocks Drafts")
        ) &&
       (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
  {
       processDescription="SandCasting";
       processSelect=1;
       machiningProcessDecision();
   }
```

```
Else
{
    processDescription=processDescription;
    processSelectio=0;
}
```

An inference engine, as depicted in Figure 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.

## 4. CASE STUDY

Planetary gearboxes are widely used in automotive and aerospace industries. We use a preliminary design of the output housing component of a planetary gearbox as an example to test the implementation of the knowledge base and agent communications. Figure 6 shows a 3-D solid model represenation of the output housing.

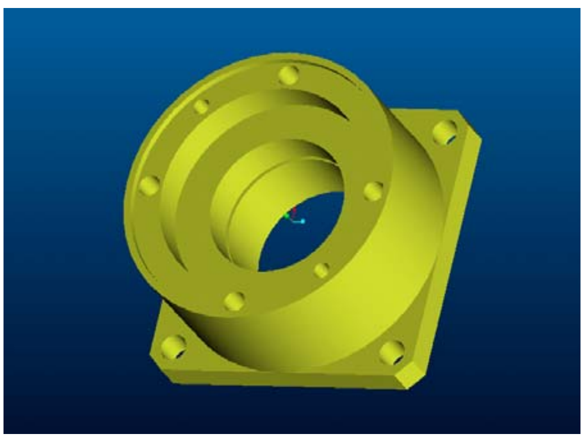

Figure 6 Solid model of the output housing

Based on the manufacturing rule in the developed knowledge base, the process planning agent generates preliminary manufacturing processes. Then, it 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. Table 1 contains the design information for the output housing component.

There are two sets of candidate preliminary manufacturing processes selected for manufacturing the output housing: ShellCasting-Turning-Drilling and PermanentCasting-Turning-Drilling. Table 2 contains the candidate manufacturing processes.

With respect to cost, the optimal preliminary manufacturing process for the output housing component is the casting-turning-drilling process. As the name suggests, this process includes three manufacturing activities: casting activity, turning activity, and drilling activity. The casting activity includes setup, handling, shell casting, load/unload and idling activity. The turning activity includes setup, handling, load/unload, cylindrical turning, big through hole boring, big blind hole boring, and idling activities. The drilling activity includes setup, handling, load/unload, small through hole drilling, counter bore drilling and idling activities. Figure 8 shows the optimum preliminary manufacturing processes and resources.

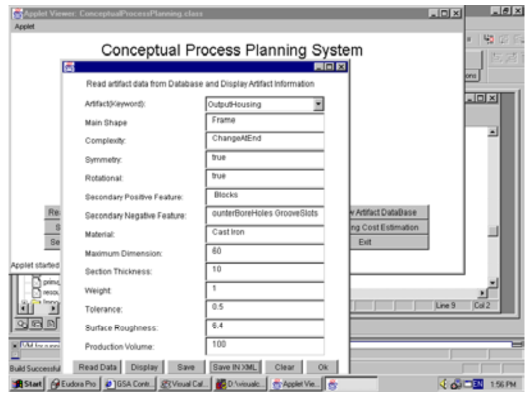


Figure 7 Artifact information from database

| | |
|---|---|
| Part name | Output Housing |
| Main shape | Frame |
| Shape complexity | ChangeAtEnd |
| Shape symmetry | True |
| Rotational | True |
| Secondary positive features | Blocks |
| Secondary negative feature | CylindricalSurface, BigThroughHoles, SmallThroughHoles BigBlindHoles, CounterBoreHoles |
| Material | Cast iron |
| Maxi dimension | 60 mm |
| Mini Section thickness | 10 mm |
| Weight | 20 g |
| Tolerance | 0.5 mm |
| Surface roughness | 6.4 µm (RMS) |
| Production quantity | 100 |

Table 1 The information for output housing

| Candidate preliminary manufacturing process | Preliminary Manufacturing Process Description |
|---|---|
| ShellCasting-Turning-Drilling | ShellCasting; Turning (CylindricalTurning, BigThroughHoleBoring, BigBlindHoleBoring) ; Drilling (SmallThroughHoleDriling, CounterBoreDrilling). |
| PermanentCasting-turning-Drilling | PermanentCasting; Turning |

| | |
|---|---|
| | (CylindricalTurning, BigThroughHoleBoring, BigBlindHoleBoring) ; Drilling (SmallThroughHoleDriling, CounterBoreDrilling). |

Table 2 Candidate manufacturing processes for the output housing

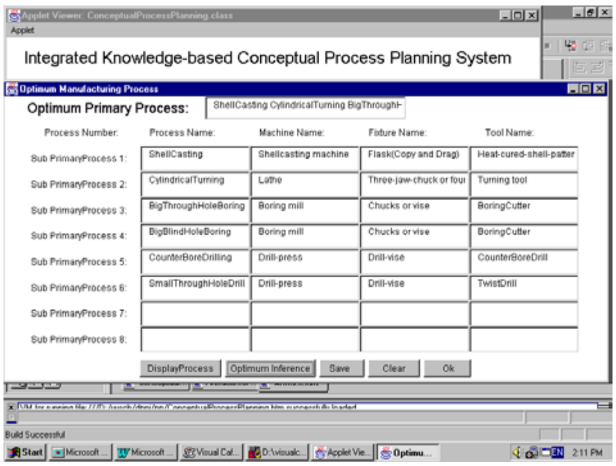


Figure 8 Optimal primary process and resources

The selected process 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).

## 5. SUMMARY 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 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, computer-aided process planning (CAPP), database, knowledge base, and mathematical-equations-solving software.

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 computer-aided design and manufacturing systems.

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