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Expert Systems with Applications 21 (2001) 99–107

Expert Systems with Applications

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# Knowledge-based parametric design of mechanical products based on configuration design method

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**Abstract**

Parametric modeling and configuration design methods are key technologies for mass customization in manufacturing. This paper describes the parametric modeling process of machine tool, and proposes a framework which parametrically models a machine tool assembly based on a design expert system. The concept of design unit, which is one level higher than functional feature, and the parametric modeling concept with functional features have been proposed. The domain knowledge in the knowledge-base has been mapped to the geometry of the CAD system. A design expert system to redesign assemblies of a machine tool has been implemented, because commercial CAD systems cannot handle the parametric design of assemblies. This system consists of a commercial expert system shell, a design knowledge-base, and a commercial CAD system with an API program. The API program interfaces the expert system with the CAD system through a GUI. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords*: Functional feature; Design unit; Configuration design; Parametric modeling; Design expert system

## 1. Introduction

The computer is an important tool to design an engineering system. CAD (Computer Aided Design) system is inevitable in design practices. It is desired to have an application that supports the entire lifecycle of initial design, configuration design, detail design, manufacturing, and disassembly. Design changes frequently through the design stages while the optimal design is supported by the engineering analyses such as static analysis, dynamic analysis, and FEM (Finite Element Method). To meet the market requirements, the old mass production system is being changed into the mass customization system. The production of a small volume with diverse product types is the new trend. The parametric modeling technique is useful when the geometric model should be changed frequently during the design process. The geometric changes of a part can also influence the assembly of the model.

Most commercial CAD systems support the parametric modeling of parts, but the parametric modeling of assembly models is not well supported. This paper proposes a framework of design expert system which is composed of a commercial CAD system and an expert system. The proposed design expert system has been applied to the parametric modeling of a machine tool assembly. This system can parametrically model the parts and assemblies of the product based on the design knowledge-base.

There have been researches about configuration design method (Brown, 1999; Franke, 1998; Kang & Han, 1997; Koo, Han & Lee, 1998; Sabin & Weigel, 1998; Yu, 1996). However, it is hard to find a configuration design system which can handle a 3D CAD geometry. Most of configuration systems are the catalog design systems, which specify properties of products such as personal computers and passenger cars. To visualize the design results, and to modify the design interactively, it is necessary to integrate the configuration system with a CAD system.

This paper introduces the feature representation, a concept of design unit, parametric modeling, and configuration design methods and proposes a framework of a design expert system which describes parametric modeling with design knowledge-base. This design expert system supports not only the configuration design but also the geometry design, and can be used from the initial design throughout the detail design. This system performs the design reasoning process when design changes occur during the parametric modeling of products. Finally, the system has been applied to the design of a machine tool assembly to verify the concept.

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PII: S0957-4174(01)00030-6

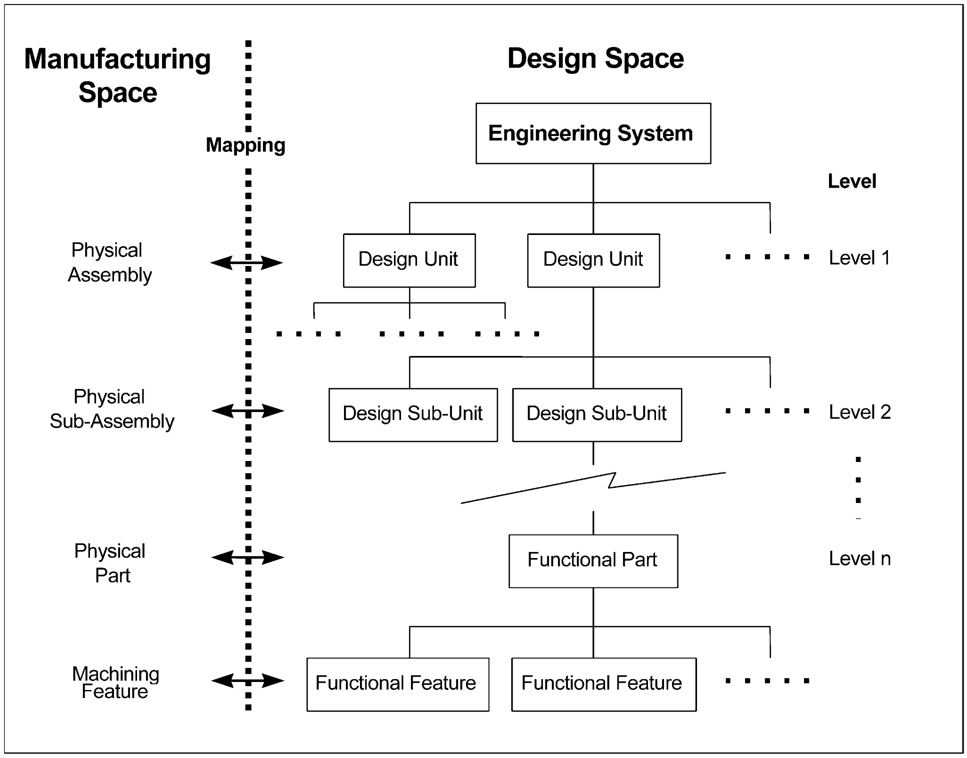


Fig. 1. Hierarchy of design units and functional features in an engineering system.

## 2. Parametric modeling of design units

Parametric modeling allows re-use of existing products and rapid design modification based on the results of engineering analysis (Shin & Kwak, 1999). In a feature-based modeling system (Regli, 1995; Salomons, 1994; Shah & Mantyla, 1995; Shah, Mantyla & Nau, 1994), the level of detail for feature classes is important. It should be decided among which level of detail they are manipulated. The different levels of detail are form features, functional features, and machining features. This paper places priority on the functional features which are used by designers, and proposes the concept of design unit to present the parametric design of assembly using functional features. Based on the concept of design unit to an engineering system design, designers modify design units when a system similar to existing one is to be designed. If a design unit is to be modified, the geometric shape or the function of the design unit should be modified. Such parametric modeling tools should allow not only modification of part but also that of assembly. The principal terminologies used in this paper are defined as follows.

1. Design unit: A unit that takes charge of a fundamental function in an engineering system. The whole system is composed of design units. A design unit is composed of design sub-units. A functional part at the lower level is composed of one or more functional features. The depth level of detail for a design unit which is made of assembly and sub-assembly can be decided by the designer as needed.
2. Functional feature: It is a feature that has importance on the function of a design, and includes not only geometric information but also design intents or functions. A functional feature can be called by different names according to the application domains. Designers usually manipulate a feature in terms of function rather than geometry.
3. Form feature: It is one level below the functional feature. It is the generic definition of a feature independent of domain. It is the basic unit, which presents geometric primitives. The machining feature also utilizes the form feature to define the geometry.

Fig. 1 shows the hierarchy of design units and functional features in an engineering system of the design space. Design units can be subdivided into several levels as needed, and each design unit is mapped onto a physical assembly in the manufacturing space. Functional features near the bottom of the hierarchy of the design space correspond to machining features in the manufacturing space. It is not the one-to-one correspondence.

There are concepts similar to the design unit proposed in this paper. Nomoto and his associates proposed the concept of unit object in the shipbuilding CIM (Nomoto, Aoyama & Tabata, 1989). The concept of unit object is to manipulate the structural unit of a ship as one object. Using the concept of unit object, a designer can easily design a part

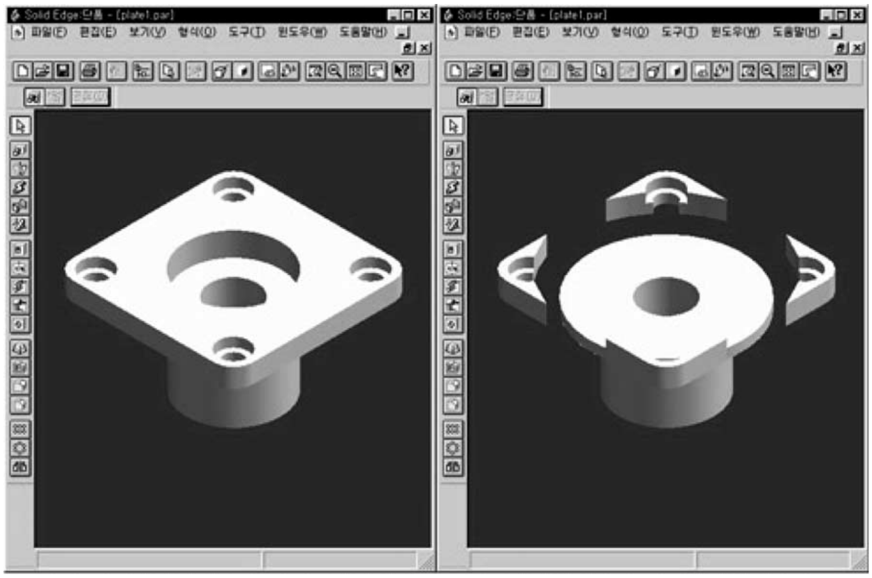

Fig. 2. Parametric modeling of a part without constraint.

by providing a small number of values of specified parameters instead of the full, enumerated description. At the Adelaide University in Australia, the concepts of design unit and functional unit have been introduced in the architectural design. The design unit represents a physical entity of a structure (building), and the functional unit represents a functional requirement which a design unit satisfies (Woodbury & Chang, 1995).

A parametric change cannot be accomplished only with dimensional changes of a model. For example, there is a plate which has a hole. If the diameter of the hole is larger than the width of the plate, it will be an undesirable modeling. Fig. 2 shows an example of undesirable parametric modeling without constraints. Dimensional constraints should be imposed between parts, and between design units. Modeling errors can be avoided by the help of the constraints.

Parametric modeling has two approaches. One is algebraic approach and the other is AI (Artificial Intelligence) approach (Verroust, Schonek & Roller, 1992). In this research, the AI-based approach using a commercial CAD system and a commercial expert system shell has been used. Geometric constraints between features, dimensions, and assemblies can be represented as rules within a knowledge-base.

## 3. Application of configuration design methodology

Fig. 3 shows a modification of the classification by Huang and Brandon (1993), where design problems fall into certain classes according to their complexity.

Class 1: The generic structure of the design artifact is unknown.
Class 2: The generic structure of an artifact is known but the specific scheme (composition and layout) is unknown.
Class 3: Both the composition and layout of an artifact are known. The product structure tree and the topology of the artifact are also known.

The three classes correspond and overlap with the design stages of conceptual, embodiment, and detail design. Class 1 is the configuration design, Class 2 is the topology design, and Class 3 is the parametric design. The principal task of a configuration design is to establish a schema which configures the product based on the pre-defined parts library. The topology design is to decide the arrangement of parts based on the generic structure of the design problem. It decides on an optimal schema and attributes of the product. The design problem of Class 1 starts from the conceptual design. This is

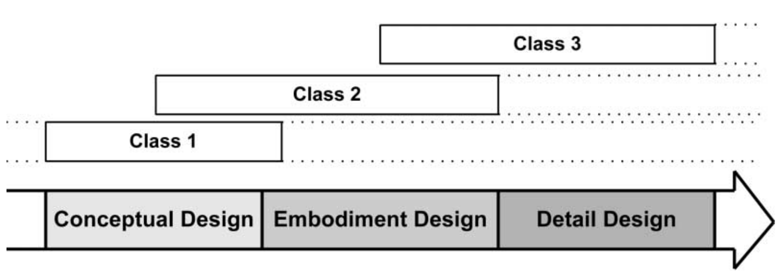


Fig. 3. Classes of problem, classes of method of design.

the most difficult stage because parts selection, generic structures of the product, and topology (relative position between part) have to be designed according to the design requirements.

Configuration design method is 'to define the relationship between parts to satisfy the constraints and the product specification (Koo et al., 1998)'. Configuration design starts from a set of parts in the initial design stage. Some of relations between parts can be given from the start. Required functions, performance, and cost can be obtained when a design proceeds with a pre-defined parts library. Knowledge about parts, knowledge about the relations between parts, attributes, and constraints of parts are the configuration knowledge.

Configuration design gives values to attributes of a part. Parts satisfy internal rules for connections or topological relationships. The configuration design is divided into two classes and the first one is pure composition (Huang & Brandon, 1993). The parts list of the product is already known and fixed during the configuration process. In the second class, parts can be substituted as the design proceeds. New parts can be generated if the suitable parts cannot be found. Spatial relationships and key dimensions should be determined. To implement the configuration process, algorithms such as checklist and decision tree are used (Koo et al., 1998). By editing the assembly tree, individual part can be easily substituted from the parts library, and design alternatives can be created without difficulty.

There are several kinds of machine tools, which are considered in this research. By dividing different machine tools into design units, we can get different sets of functional decompositions. But there are common functional units. The configuration design can be performed using the parts library which is constructed for the design of machine tool.

The experimental application of the configuration design method for a machine tool is explained as follows. A horizontal machining center can be decomposed into design units of bed unit, column unit, index unit, spindle unit, guide unit, and automatic tool changer unit.

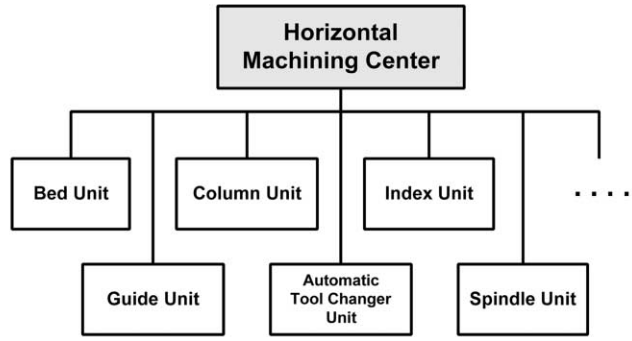


Fig. 4. Design units of horizontal machining center (first level).

Fig. 4 illustrates design units of the horizontal machining center. After the horizontal machining center is decomposed into design units of the first level, it can be further decomposed into sub-units. Finally, it can be decomposed into functional parts level. Combination of design units or parts, which satisfies the design requirements and constraints, can constitute the entire system. Fig. 5 shows the 3D model of the horizontal machining center (Kwak, Han et al., 1998), which develops the Tongil Heavy Industry.

## 4. Design reasoning in parametric modification of an assembly using the expert system

To construct geometric models, designers use design knowledge and heuristics. For the parametric modeling of an assembly, an expert system can handle design constraints. Because the inference engine and the knowledge-base are separated in an expert system, it is easy to add or modify knowledge pieces inside the knowledge-base. In this respect an expert system is

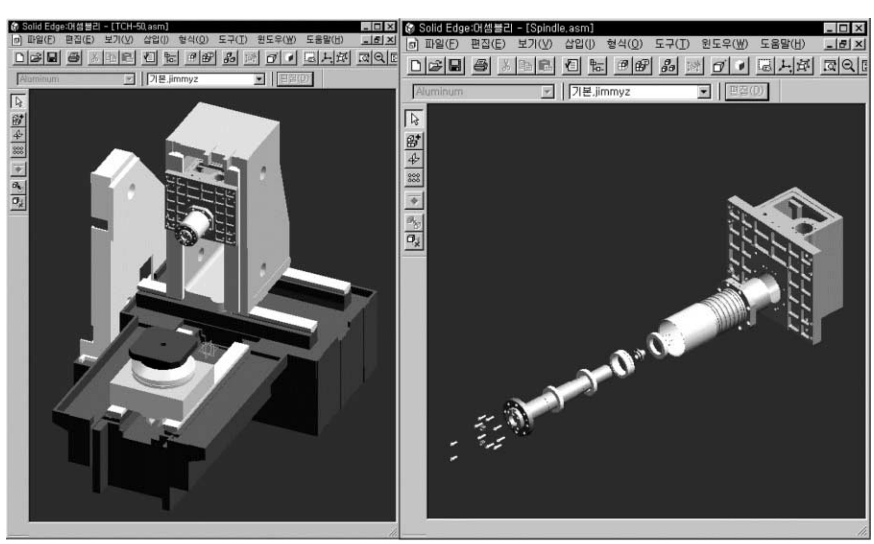

Fig. 5. The horizontal machining center.

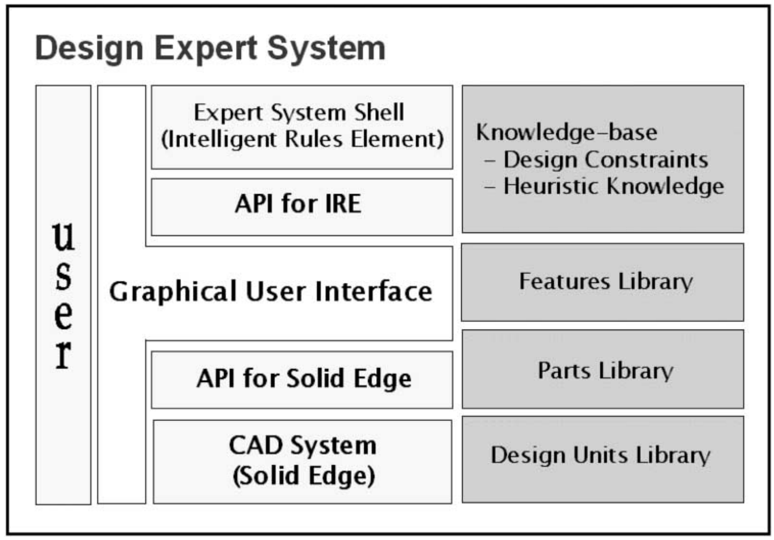


Fig. 6. System architecture of the design expert system.

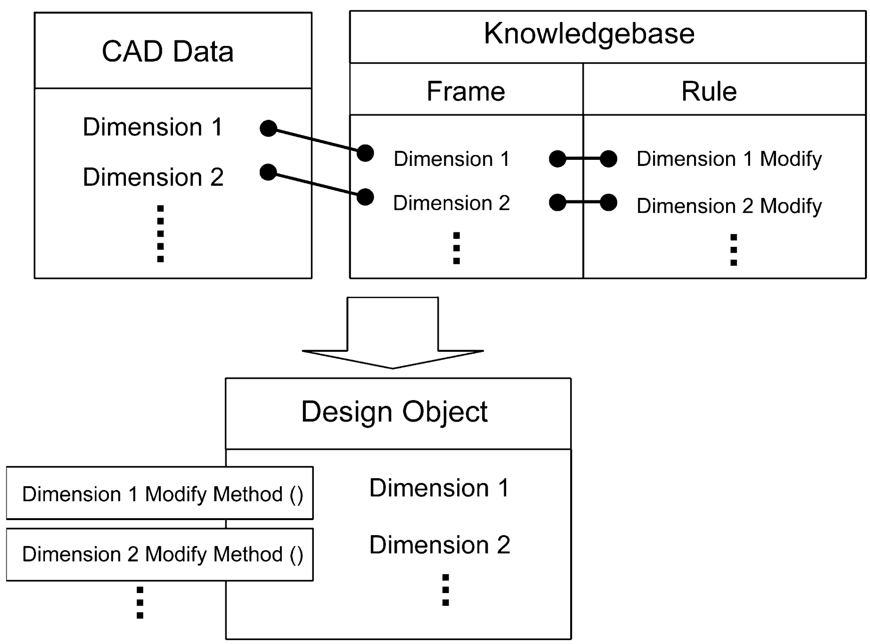


Fig. 7. Association of CAD data and knowledge-base.

different from an inference system based on procedural algorithms. Several researches in the engineering design area apply knowledge-based system and AI methods (Bok, Myung & Han, 2000; Mcalinden, Florida-James et al., 1998).

The knowledge-base of the proposed design expert system stores the following knowledge.

1. Knowledge for the configuration design; topology design, parts selection, and parts arrangement.
2. Design constraints for parametric modeling and inference.
3. Feature attributes.
4. Heuristic knowledge of design.

Fig. 6 shows the architecture of the design expert system. Knowledge-base, features library, parts library, and design units library are the main components of the system. The implemented design expert system consists of a commercial expert system shell, a commercial CAD system, and an API (Application Programming Interface) which integrates the entire system. Intelligent Rules Elements (IRE) V4.0 of Neuron Data (1997) is used as the expert system shell and Solid Edge V4.0 of Unigraphics Solutions (2000) is used as the 3D CAD system.

Fig. 7 shows the relationship between the design knowledge-base and the CAD data. The design information is processed by the methods inside design objects.

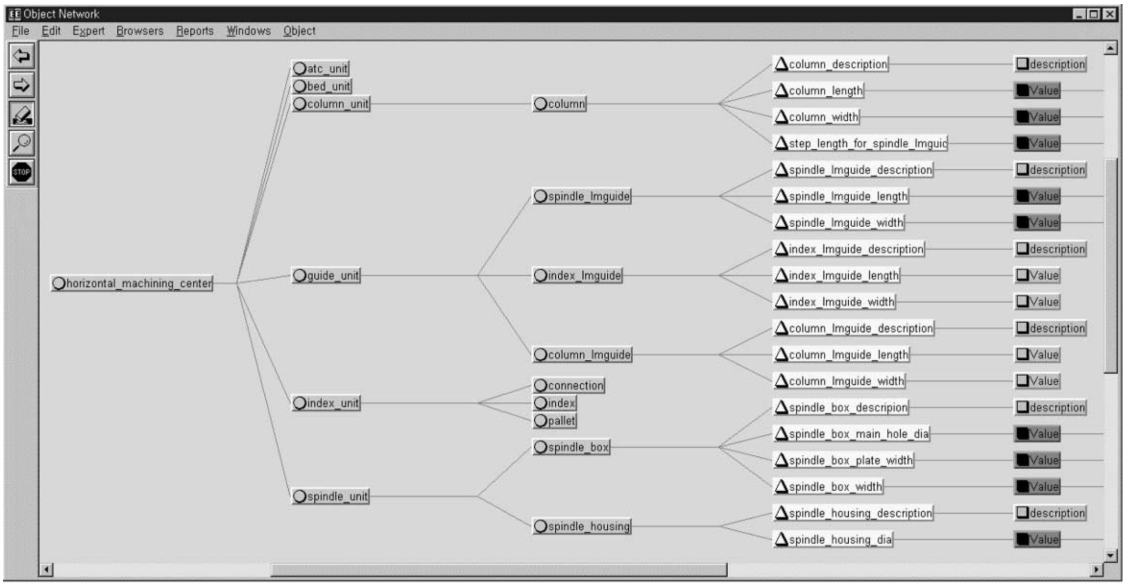


Fig. 8. Object network of the horizontal machining center.

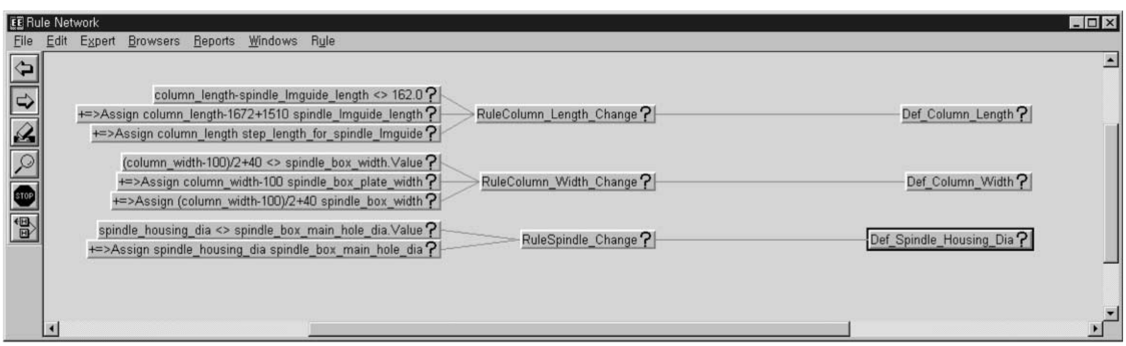


Fig. 9. Rule network in the design knowledge-base for the horizontal machining center.

The object network of the horizontal machining center is shown in Fig. 8. We can see the product structure of the machine and component properties. Fig. 9 shows the rule network for the design reasoning. The inference engine finds and triggers the rule to chain out the reasoning process.

The rules in the knowledge-base are used to process the data representation of the machine tool product. This representation is made of interrelated objects as shown in Fig. 8. They constitute the representational dimension. As graphically expressed in Fig. 10, the representational dimension intersects the reasoning system at the data level (Neuron Data Inc., 1996).

Fig. 11 shows three rules in the knowledge-base for the horizontal machining center design. Within the first rule, dimensions of 'column_length', 'spindle_lmguide_length.-Value' and 'step_length_ for_spindle_lmguide' of the horizontal machining center are related each other. If the designer changes 'column_length', the design expert system changes 'spindle_lmguide_length. Value' by the dimension of 'column_length-1672 + 1510', and also changes 'step_length_for _spindle_lmguide' by the dimension of 'column_length'. This kind of reasoning process occurs frequently during the design process of machine tool design. Designer can easily modify his/her product model by this reasoning process.

Fig. 12 shows the user interface of the design expert

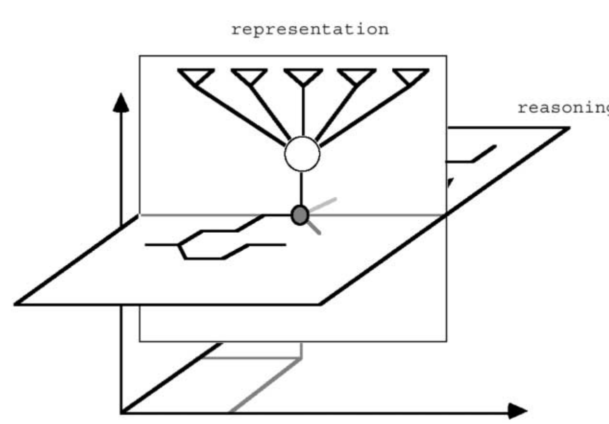


Fig. 10. Intersection of the Reasoning and Representation.

```
(@RULE=   RuleColumn_Length_Change
          (@LHS=
                    (<>       (column_length)     (spindle_lmguide_length.Value))
          )
          (@HYPO=   Def_Column_Length)
          (@RHS=
                    (Assign   (column_length-1672+1510)    (spindle_lmguide_length))
                    (Assign   (column_length)     (step_length_for_spindle_lmguide))
          )
)

(@RULE=   RuleColumn_Width_Change
          (@LHS=
                    (<>       (column_width)      (spindle_box_width-100))
          )
          (@HYPO=   Def_Column_Width)
          (@RHS=
                    (Assign   (column_width-100)  (spindle_box_plate_width))
                    (Assign   ((column_width-100)/2+40)    (spindle_box_width))
          )
)

(@RULE=   RuleSpindle_Change
          (@LHS=
                    (<>       (spindle_housing_dia)        (spindle_box_main_hole_dia.Value))
          )
          (@HYPO=   Def_Spindle_Housing_Dia)
          (@RHS=
                    (Assign   (spindle_housing_dia)        (spindle_box_main_hole_dia))
          )
)
```

Fig. 11. Rules in the design knowledge-base of machine tool design.

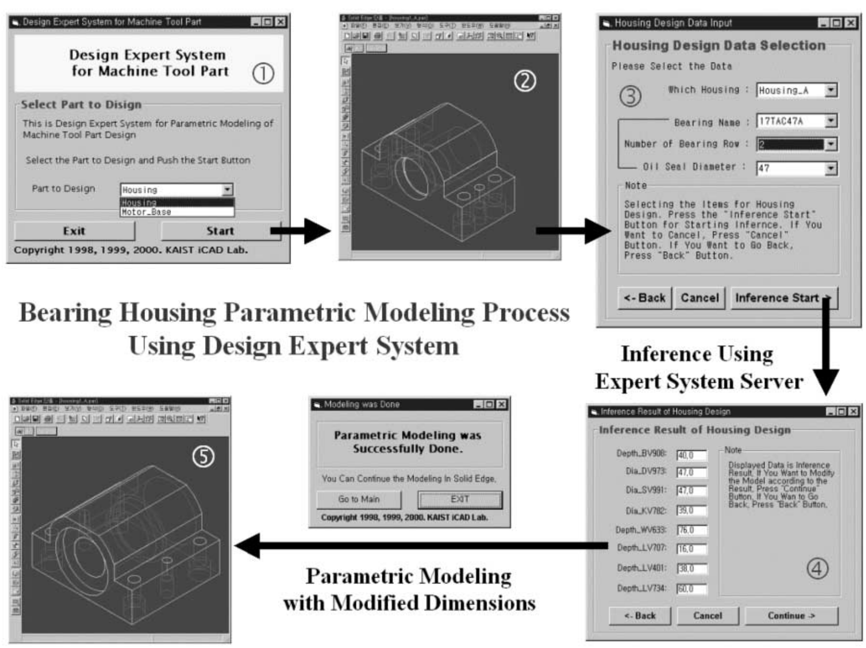


Fig. 12. Parametric modeling process of bearing housing using the design expert system.

system which is developed using the MS Visual Basic 6.0, the API for Solid Edge, and the API for the expert system shell IRE. Following steps shows the parametric modeling process of Fig. 12 for a bearing housing which is a design unit of the machine tool.

The system first loads the part selection window as shown in step (1), and the designer selects the part (bearing housing) to be designed. The Solid Edge 3D CAD system loads the standard 3D model for the bearing housing as shown in step (2). In the window for the design data selection as shown in step (3), the designer can select the type of bearing housing, the type of bearing, and optional values. Then the designer initiates an inference using the design knowledge-base inside the expert system server. As shown in the window (4), the system displays the inference results. Then the Solid Edge 3D CAD system changes the design

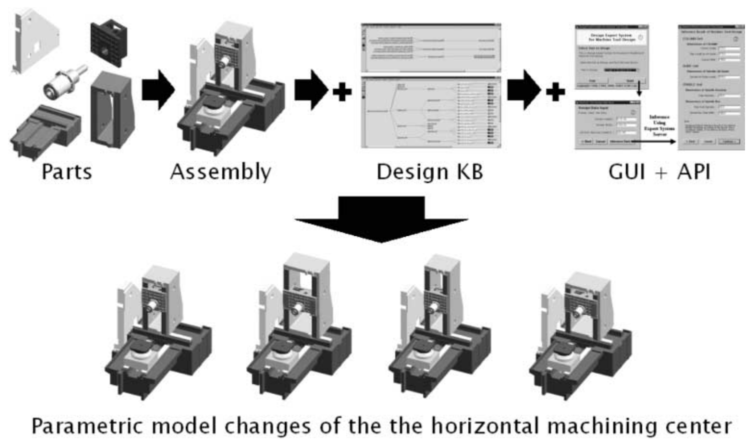


Fig. 13. Build up process of the design expert system for the parametric modeling of assembly.

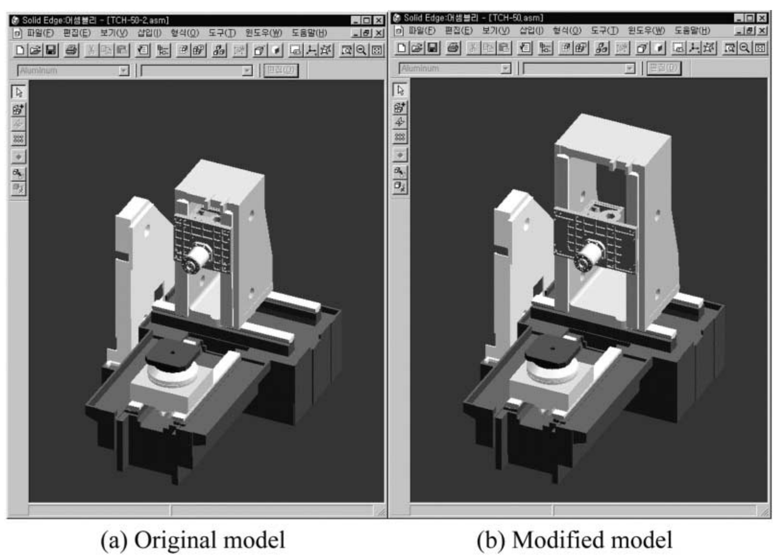


Fig. 14. Parametric modeling of the column unit and the spindle unit of horizontal machining center.

geometry based on the inference results. Parametric model change based on the modified dimensions of the bearing housing is completed as shown in (5).

To implement the parametric modeling of machine tool assembly, following steps have to be taken.

1. Modeling the parts.
2. Making an assembly with the parts.
3. List up all critical dimensions for the parametric modeling and naming the dimensions.
4. Making the design knowledgebase which contains the parametric relations of each dimension and formulae.
5. Making GUI program and API program for connecting the CAD system and the inference engine and the knowledgebase.

Fig. 13 shows the build up process of the design expert system the parametric modeling of assembly.

Fig. 14 shows the results of parametric model change of machine tool assembly. Three design units of column unit, guide unit, and spindle unit are involved in this design change. The length and width of the column and the outside diameter of the spindle housing have been changed. If the length of the column is changed, the length of LM (Linear Motion) guide, which is attached to the column and holds the spindle unit, should be changed. The step length of the column that fixes the LM guide should also be changed. If the width of column is changed, the length of the plate part of the spindle box, which is included in the spindle unit, should be changed. In Fig.14, (a) shows the original model of the column units, and (b) shows the modified model with parametric changes. Because the dimension of the outside diameter of the spindle housing has been changed, the dimension of the inside diameter of the spindle box hole should also be changed.

## 5. Conclusion

In this research, (1) a method for integrating the initial configuration design and the detail CAD design has been proposed, (2) an architecture of the parametric design expert system based on the design unit concept and the design knowledge-base has been proposed, (3) the proposed system has been tested with an assembly of a machining center.

The proposed system can parametrically change assemblies, whereas the commercial CAD systems can handle parts geometry. Parametric modeling of assemblies requires the reasoning process based on heuristic expert knowledge.

The proposed system can reduce the time for design modifications. The parametric changes are based on the knowledge-base which contains constraints between parts. With the proposed system, the modified product model can be quickly obtained through the design reasoning process. The pilot system of intelligent CAD systems is illustrated with an experiment.

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