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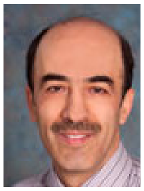

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An Expert System Approach for Selecting a Multitasking CNC Machining Center

ABSTRACT

In the selection of multitasking computer numerical control (CNC) machining centers, numerous features and complex configurations have to be considered. This paper presents the development of a knowledge base for an expert system decision support tool that identifies multitasking characteristics together with the make and model of advanced multitasking CNC centers. Knowledge acquisition is conducted using technical data sheets from major machine tool builders as a basis for the development of a structured rule-based expert system. The proposed system offers a graphical user interface function for data collection and display of decision outcomes. The developed system was validated using data collected from several machine tool builders. System testing shows satisfactory preliminary results in the configuration of multitasking CNC machines and the selection of a make and model. The system can be extended in terms of adding new machine features, makes and models. An example of user consultation demonstrates the feasibility of the developed expert system for industrial applications.

Introduction

The integration of various material removal operations into multitasking machine (MTM) tools has been accelerated in recent years by machine tool builders and has been attested by numerous articles and displays in manufacturing trade journals and industrial exhibitions (Lorincz, 2011; Waurzniak, 2013). Advances in computer technology and applications in the manufacturing industry have transformed these systems from stand-alone production units into complex integrated production centers. These systems can lead to significant savings in manufacturing operations owing to their ability to produce a variety of components in larger numbers and a multitude of features and geometries without the need for multiple setups and inter-machine part transfers. Certain specific capabilities of MTMs are described as follows:

- simultaneous shaping of two or more identical parts
- simultaneous shaping of non-identical parts
- milling of angled surfaces on cylindrically shaped parts
- multiple operations: milling, turning, grinding, etc.

Although the significant benefits of MTMs have attracted the attention of a large sector of the manufacturing industry, including automobile parts manufacturers and mold and die makers, these machines represent a major capital investment, particularly for small manufacturing shops. Therefore, the selection of an MTM system for the correct application and at the right price is an important decision for a company. If this decision is not properly made, it could lead to significant unfavorable outcomes in terms of user satisfaction and the length of time required to gain sufficient return on investment. As Lorincz (2011) noted, the savings in setup time, increased part accuracies, and reduced inventories can be substantial if the machinery properly matches the application. Furthermore, with increasing levels of sophistication in features and options, manufacturing engineers and managers face a nontrivial task in configuring and selecting an MTM. No industry-wide standards currently exist, and decision-making depends on the knowledge and advice of human experts. This situation calls for the automation of knowledge via a decision support expert system.

At present, relatively few academic studies on decision support systems have been conducted for machine tool selection. Many of the existing studies have focused either on selection methodologies or selection based on general machine features. For instance, in one study, Gopalakrishnan et al. (2004) discussed a two-phase decision support system for machine selection: a base machine selection and detailed options selection. Factors such as the cost and size of each machine, available floor space, and the sizes of parts and fixtures were considered for the base machine selection. The detailed options selection phase considered aspects such as high speed, high accuracy, and complexity of cutting. In another study, Arslan et al. (2004) suggested a similar decision support system for machine tool selection by creating a sample database for a limited number of machine tools and applying a multi-criteria weighted average method to rank the alternatives. The database included information on the machine type and size, spindle, tooling, work support, and axis of motion. The selection criteria consisted of precision, cost, reliability, safety, space, flexibility, and productivity. A study by Selvaraj et al. (2006) highlighted the suitability of MTM systems in the aerospace industry, where component designs change frequently and machines must be able to adapt to each situation. The authors created a guideline for the selection of b-axis mill-turn machines. In a study conducted by Chowdary (2007), an artificial neural network model was proposed as a cost-effective solution to the machining center selection problem. Several parameters were incorporated into the model, including the machine size, number of tools, tool changing time, spindle power, and price. Lin and Yang (1996) proposed an analytical hierarchy procedure for the selection of conventional and computer numerical control (CNC) material removal machines. The procedure involved the evaluation of basic factors such as manufacturing lead-time, labor cost, and operation shifts. Chtourou et al. (2005) presented a prototype rule-based expert system for the allocation of production equipment to manufacturing operations based on part routings and demand data. Tansel and Yurdakul (2009) applied a fuzzy technique to develop a decision support tool for machining center selection. This support tool considered several criteria, including the spindle speed, machine power, tool-changing time, number of tools, and table size.

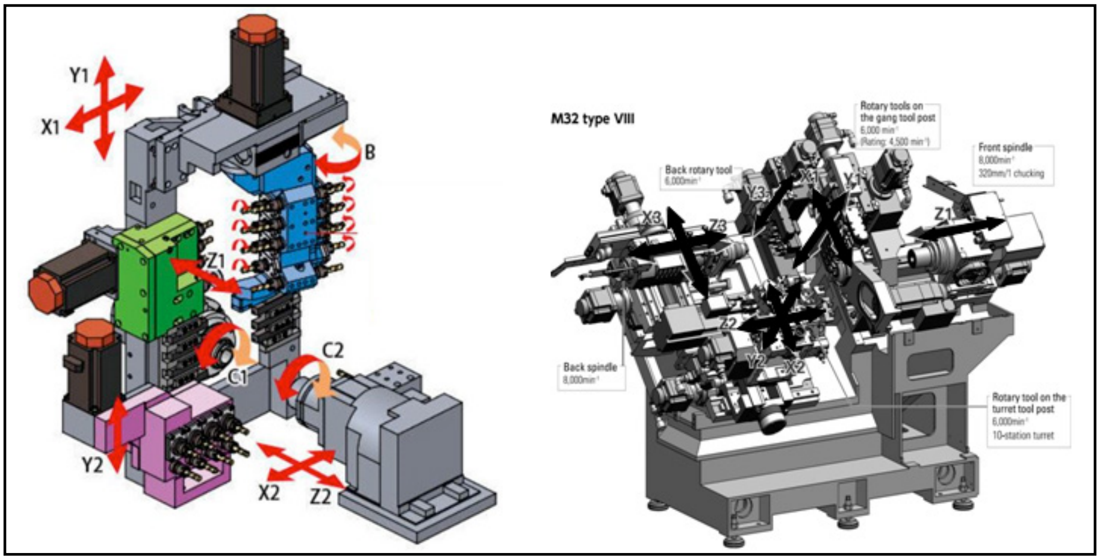
These studies were typically limited to the generic features of machine tools, selection of a subset of machine tools, or machines for applications other than material removal. To the author's best knowledge, no publication exists that reports the application of decision support methodologies in the selection of advanced multitasking CNC machines. Because MTM machines are more complicated than general machine tools, the case addressed in this paper involves the selection of numerous complex configurations, some of which were presented in a study by Djassemi (2009). In that study, a taxonomy of MTM types was presented based on the number of axes of motion, tooling, and spindle subsystems. The author proposed a set of guidelines for selecting an MTM and noted the need for further research in the development of a knowledge-based expert system to capture the many variations of MTM configurations. This subject forms the framework of this study, in which a decision support expert system is developed to assist users in the configuration and selection of multitasking CNC machining centers that meet certain production goals.

Multitasking Attributes

For the purpose of this study, a multitasking CNC machine is defined as a material removal technology that is capable of performing simultaneous and/or sequential milling and/or turning operations with two or more cutting tools in action simultaneously. Most multitasking machining systems contain five or more axes of motion and are capable of utilizing any combination of the three primary linear axes (X, Y, Z), three primary rotary axes (a, b, c), and/

or additional axes parallel to the primary ones. This group of machines is commonly equipped with two or more tool systems and spindles and can operate in synchronous or asynchronous machining modes

Figure 1. Examples of multitasking CNC machining/turning centers. Adapted from http://www.tsugami.co.jp/ and http://cmj.citizen.co.jp.



With the continuous development of new machining methods and options, users must determine the type and configuration of MTM that best matches their requirements. Although most MTMs can be identified as either milling- or turning-type machines, a hybrid MTM can be composed of a wide range of functions, such as turning, milling, contouring with the c-axis, off-center machining with the Y-axis, milling of angled surfaces with the b-axis, and grinding. Table 1 lists the major multitasking features developed to date by MTM builders.

Table 1. Multitasking Features of CNC machining centers

FEATURE	FUNCTION/PURPOSE
Y-axis with turret	Production of more complex parts with features that are not on the centerline (off-center features).
Twin-spindle with *b*-axis	The *b*-axis is a tool spindle with the ability to change tools, as in a vertical mill. A *b*-axis tool spindle can change to any angle.
Backworking spindle	Transfer of the work from the main spindle to a sub-spindle. A tool turret is used to machine the back end of the part.
Three turrets	Large tool-holding capacity for production of a family of parts with complex features plus cycle time reduction.
Rotary *b*-axis	Angular cuts by a *Y*-axis spindle.
Y-axis with/without ATC	Milling tool on a lathe with ATC; milling tool on a lathe without ATC.
Multi-spindle	High-volume production runs and cycle time reduction.

Note: ATC stands for automatic tool changer.

Research Approach

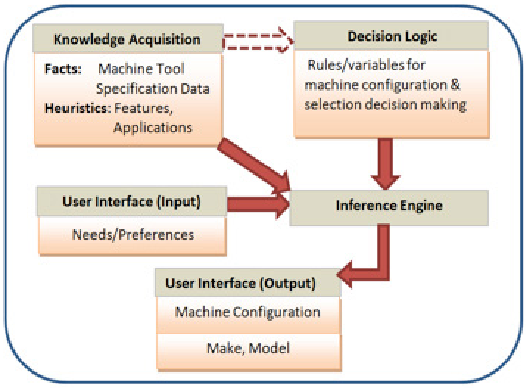
An expert system is an interactive computer-based decision tool that applies both facts and heuristics to address difficult decision problems founded on the knowledge obtained from an expert (Ipek et al., 2013). The expert system method has been applied for selection decisions across various fields. Certain recent examples of specific tasks undertaken by expert systems are:

- materials selection (Ipek et al., 2013)
- machine tool selection (Tansel and Yurdakul, 2009)
- rapid prototyping system selection (Masood and Soo, 2002)
- die- and mold-making operations (Cadir et al., 2005)
- cutting tool selection (Arezoo et al., 2000)
- material handling equipment selection (Chan et al., 2001)

In this study, a prototype multitasking expert system (MTES) for the configuration and selection of multitasking CNC machining centers was developed using the Corvid (Exsys, Inc.) expert system development tool. In addition to its functionality and ease of programming, the license pricing for academic research was also a major factor in selection of Corvid for this study.

The proposed decision support system operates based on a rule-based logic reasoning method, one of the most widely used knowledge representation and reasoning methods (Ligeza 2006, Gopalakrishnan et al., 2004, Tan et al., 2015). While a traditional decision tree can be used for cases involve small data sets with limited number of variables, a ruled-based expert systems is more suitable in assisting decision making involving complex conditions with multiple variables/features such as the selection of multitasking CNC machining centers. The developed ruled-based expert system consists of four main modules: (1) a knowledge acquisition module containing multitasking CNC machine tool information; (2) a decision logic module containing application-specific rules; (3) a user interface that collects inputs; and (4) an output graphic display. These modules are connected through the inference engine of the Corvid expert system shell which executes the decision rules and generates recommendation(s) deduced from the logics embedded in the rules. Figure 2 shows the framework of MTES, adapted from the general architecture of expert systems. To verify the functionality of the developed system and accuracy of its output, interactive consultations will be applied.

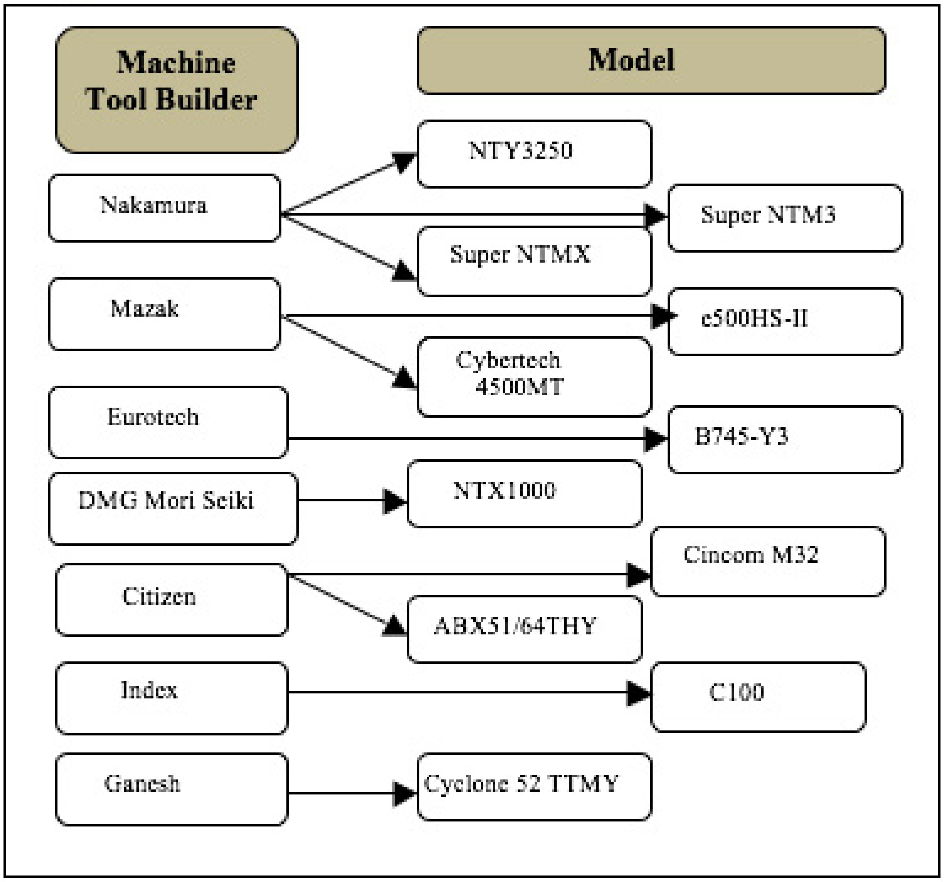
Figure 2. Framework of multitasking CNC expert system.



Knowledge Acquisition

The knowledge acquisition process acquires sufficient knowledge to build a knowledge base. The knowledge base component of MTES encompasses multitasking features, such as those listed in Table 1, although additional features can be incorporated by the users. In MTES, knowledge management involves the encoding of knowledge compiled from machine tool data sheets, part geometry and material machining heuristics (some of which are described in Table 1), into If-Then rules. The scope of the knowledge base in the proposed MTES includes major machine tool builders and a number of multitasking CNC machine models, as shown in Figure 3.

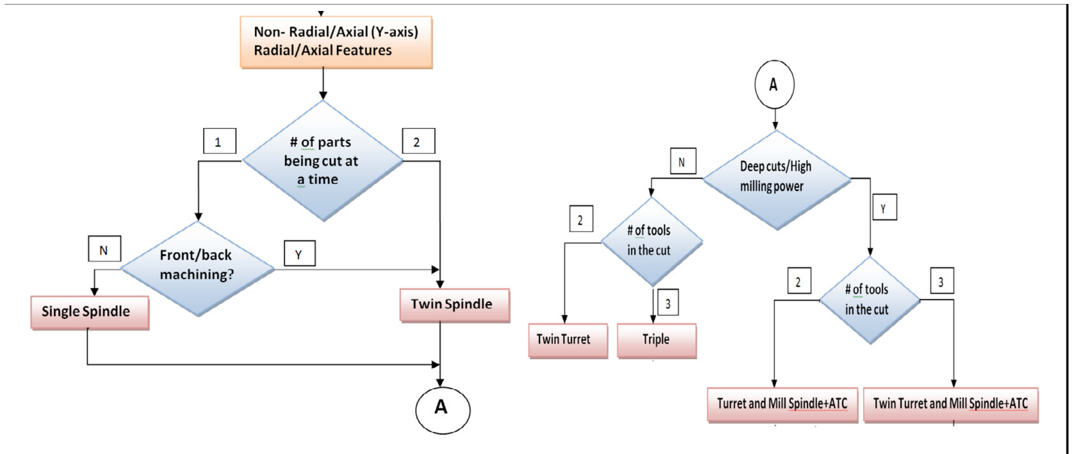
Figure 3. Multitasking CNC machine manufacturers and models.



Decision Logic Reasoning Process and Rules

The decision logic diagram is the foundation of rules development in expert systems. Sections of the diagram developed for MTES are shown in Figure 4. The geometrical features of a part and the production goals are examined in various stages and, based upon the options chosen by the user, a related machine feature is selected. For example, if "a machine with high power for deep cutting" and "reducing cycle time" are desired, a "single turret with mill spindle" feature is recommended.

Figure 4. Sections of a logic tree in multitasking CNC expert system.



After encoding the logic into the rules, the inference engine of the expert system shell interprets the produced rules, interfaces the user input with the knowledge base, and generates an output decision. The inference engine drives the system through a forward chaining strategy, as illustrated in Figure 5. The process begins with known facts from the knowledge base and user input, and works forward to identify whether a decision can be reached.

Figure 5. Forward chaining decision making process

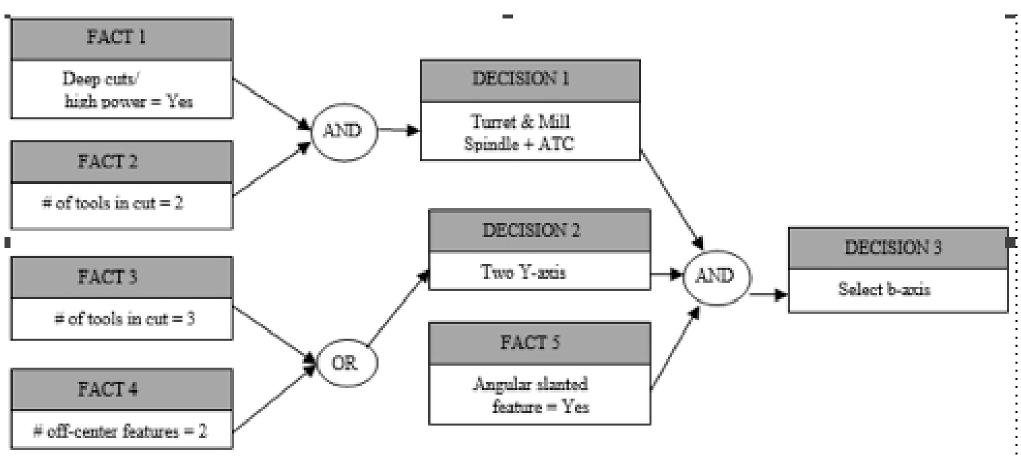
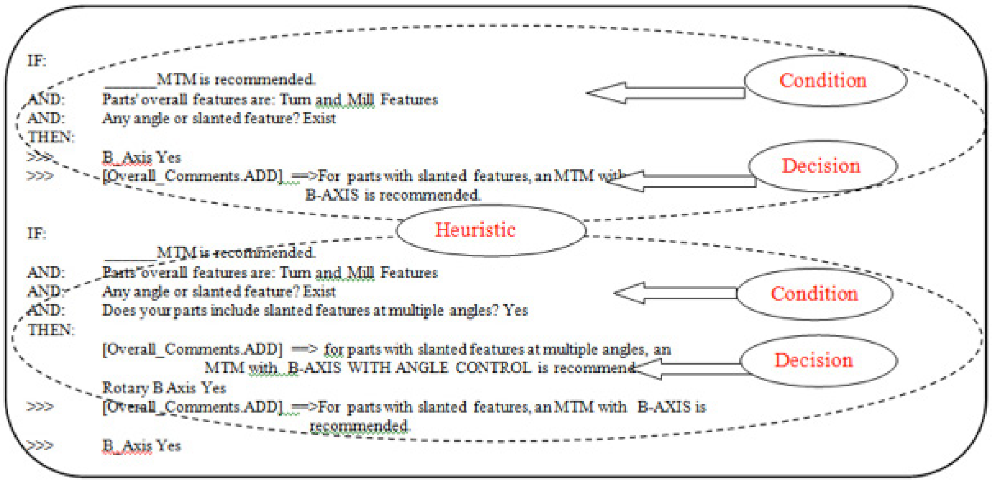


Figure 6 shows the structure of typical rule sets in MTES. Each set is intended to examine one or more multitasking attributes of MTMs. In these rules, the "If" part includes conditions, and the "Then" part is composed of decision statements. In rule-based representations of knowledge, each expert "rule of thumb" is known as a "heuristic". A heuristic is a specific small fact that instructs a portion of the decision. Combination of all the heuristics allows the overall decision-making problem to be solved (Corvid System, 2011).

Figure 6. Rules and heuristics structure in expert system.

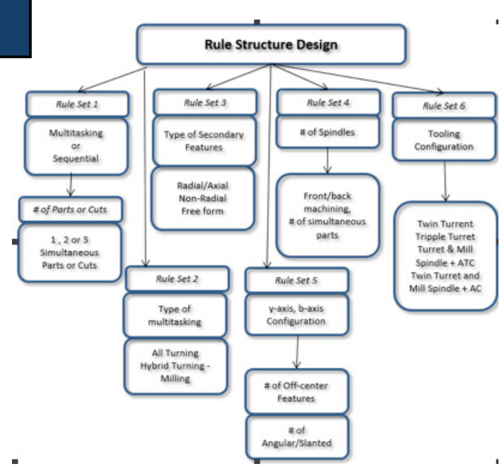


When a user initiates a consultation session, the inference engine examines a rule and evaluates the associated conditions. If the conditions are met, a decision statement (a multitasking feature in this case) is added to a list of recommendations. If the conditions are not met, the inference engine seeks another rule within the defined rule sets. In a sequential manner, all rules are evaluated and multitasking options are appended to a recommendation list whenever a related condition(s) is met.

Based on the constructed decision logic and acquired knowledge, six sets of rules were generated for MTES (Figure 7). These rules represent knowledge associated with various multitasking features of CNC machining centers, as described in Table 1. For example, rule set #5 is developed to determine whether a decision for recommending Y-axis and b-axis machine features can be made based on the number of off-center and angular geometrical features of the part.

The developed MTES was tested by running consultation trials to ensure that the imbedded rules are individually and collectively complete and produce the correct results. An example of a user consultation session is illustrated in the next section.

Figure 7. Rule hierarchy design in MTES.



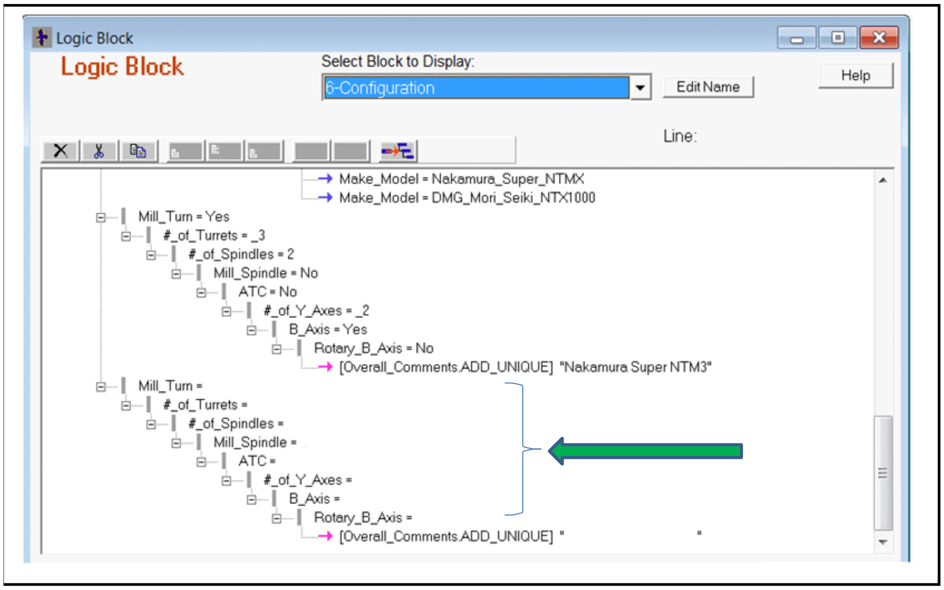
User Interface

The output from the consultation includes descriptions of a set of machine multitasking features together with a manufacturer make and model that offers such features. Interaction between the user and the MTES is supported through a graphical user-system dialogue. The system is designed to be interactive, user-friendly, and straightforward. The question window displays the question at each step together with visual aids that assist the user in choosing the best multitasking option. The system asks focus-relevant questions and offers advice and recommendations based on the input and the underlying heuristic rules. The recommendation window contains two sections: the recommended configuration and the recommended make/model.

System Extensibility

The developed expert system can be extended in terms of adding new machine features and machine makes and models. Figure 8 shows a subset of rules for the selection of make and model based on the specifications of the machines. As a template, a set of existing rules can be readily copied and pasted at the end of the machine configuration page. In the case of a new feature, the appended rules can be modified to match the features of the added machine.

Figure 8. Extensibility of knowledge base in expert system. Note: Arrow points to a template for appending a new machine's specifications.



RESULTS AND DISCUSSION

Two consultation trials are presented here for preliminary validation of the developed expert system and the results are shown in Figures 9 to 11. Figure 9 shows a snapshot of the selected user input screen. The system asks multiple-choice questions for which the user chooses one of the available options. The question-answer session continues until a recommendation is made. The output screen delivers descriptive recommendations for the multitasking features. As shown in Figure 10, a short list of MTM makes and models that closely match operational requirements can be generated by the system. In the second consultation trial, a few operational requirements are modified. As shown in Figure 11, the system recommends two machines that are different from the first trial. In the case wherein more than one machine meets a set of requirements, as in the example, the cost and size of the machines can be taken into consideration to rank the choices. To this end, future work will attempt to extend this knowledge with a cost-benefit analysis for the addition of various multitasking features to the base machine.

Figure 9. Input screen of consultation trial #1. (Source of images: Zelinsky 2011)

Figure 10. Output screen: recommendations of expert system.

An overview of similar work in published literature (Chowdary, 2007, Gopalakrishnan et al., 2004, Tansel and Yurdakul, 2009) indicates that the numerous multitasking features of CNC machines that are incorporated in MTES have not been considered in previous work. The decision support system presented in these studies typically limited to basic machine features such as speed, power, table size, cooling system and cost. As can be seen in Figure 10, based on the user's needs, MTES recommends a machine with "twin spindle", "triple turret" and "three Y-axis". Based on these multitasking features the system has identified two makes and models.

Although the developed system is limited to machine tool data and multitasking features captured for system development purpose, the knowledge base can be extended by appending rules using the embedded templates as new features, and new makes and models can be introduced by machine tool builders. The author believes that the features of the multitasking CNC machine offer multiple capabilities and flexibilities that will enable companies to be responsive to market demands at a cost that is insignificant over the life of the machine.

Figure 11. Results of consultation trial #2.

CONCLUSION

This paper presented a structured rule-based expert system prototype designed for knowledge acquisition and facilitating decision-making for the configuration and selection of multitasking CNC machines. The proposed system can provide large savings in time and investment cost for this complex technology by reducing the alternative configurations that do not meet production requirements. The developed system was validated through data collected from several machine tool builders. This study can be extended by developing expert systems to allow the user the option of prioritizing features based on production goals and subsequently ranking the recommendations based on a weighted score.

A digital copy of the developed expert system is available to industrial or academic users upon request. The users can download an evaluation copy of the software from the supplier's web site (Corvid System, 2011).

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