# PETRI NET-BASED KNOWLEDGE ACQUISITION FRAMEWORK FOR CAPP

**Roman Stryczek**

Summary

A tendency has existed over the years for Computer Aided Process Planning (CAPP) system methodologies to develop towards expert system applications. Knowledge-based expert system platforms include a knowledge acquisition module. This paper presents the binary Petri net as a unified framework for acquisition and representation of knowledge in the scope of machining operations planning. An illustrative example of the process of hole-making was used to demonstrate the graphical user interface.

Keywords: CAPP, knowledge acquisition, user interface, Petri net

**Sieć Petriego jako platforma akwizycji wiedzy dla potrzeb CAPP**

Streszczenie

Zmiany w metodologii systemów komputerowego wspomagania projektowania procesów ukierunkowane są od kilku lat na zastosowanie systemów ekspertowych. Platformy systemów ekspertowych, których podstawą jest wiedza uwzględniają moduł akwizycji wiedzy. W artykule przedstawiono binarną sieć Petriego jako zunifikowaną platformę dla akwizycji i reprezentacji wiedzy projektowej z zakresu projektowania zabiegów obróbki. Dla zilustrowania wizualnego interfejsu użytkownika podano przykład z zakresu obróbki otworów.

Słowa kluczowe: CAPP, akwizycja wiedzy, interfejs użytkownika, sieci Petriego

## 1. Introduction

Process planning is the systematic determination of detailed methods by which work pieces can be manufactured economically and competitively from initial stages to finished stages [1]. Computer aided process planning is used to interpret product/part design data in terms of features, analyze the shape, size, tolerance, location, orientation and relationship of various geometric features on a part, and translate them into manufacturing operation instructions in optimal process sequences [2]. Based on a manufacturing engineer's experience, manual process planning is very time-consuming and the result is very dependent on the person responsible for the planning. CAPP uses almost the same steps taken in manual process planning, it requires very short time compared to manual process

Address: Roman STRYCZEK, D.Sc., Eng., University of Bielsko-Biała, Willowa 2 St., 43-309 Bielsko-Biała, phone (+48 33) 8279213, e-mail: r_stryczek@poczta.onet.pl

planning and the result is dependent on the knowledge stored in the knowledge base of the CAPP system. CAPP systems initially evolved as "variant", based on standard process planning and group technology. Today, at the next stage of evolution – generative CAPP, process planning decision rules and features are built into the system. A fundamental difference exists between the variant and the generative method of manufacturing process planning. In the case of variant methods, knowledge is coded in standard processes representing each group, whose manufacturing processes are similar. In the case of generative systems, knowledge about manufacturing processes is stored in knowledge bases [3]. One of the primary tasks of a machining process planning system is to interpret the design information and prescribe appropriate machining operations consistent with the requirements set forth by the designer. Thus the general problem setting in machining operation selection and sequencing may be considered as a pattern classification task.

Built as knowledge processing systems, CAPP systems are subject to the same knowledge engineering issues as most expert systems. Therefore, they are characterised by typical phases of expert system construction, including knowledge acquisition, the usual expert system construction tools plus typical categories of declarative and procedural knowledge. The structure of CAPP systems consists of typical expert system modules, such as: a knowledge acquisition module, a manufacturing process knowledge base, an inference engine and an explanation system, which next to CAD and CAM systems interface and modules for generating manufacturing documentation constitute the basic modules of the systems.

Technological knowledge is a dynamic set of information on the manufacturing process, carried out within the strictly defined realities of a given production plant [4]. Depending on the subject or task which it concerns [5], CAPP system knowledge can be divided into the following categories:

- knowledge concerning the machined object (type of part, material, dimensions, mass, etc.);
- knowledge concerning setups and machining operations;
- knowledge concerning the quality of product finishing (surface, tolerance);
- knowledge concerning the machining means of specific basic machined forms (EFO, features);
- knowledge concerning production means (machines, fixtures, tools, etc.).

A discussion about the various forms of knowledge and its influence on the integration process in integrated, intelligent process planning systems has been presented in [6]. The role of knowledge as an integrating factor has been underscored in [7]. In expert systems, knowledge can be precise and certain or fuzzy. In the latter case, the level of difficulty increases in the construction of the expert system and especially, the user interface. Such systems are also not as well accepted by the direct user [8]. Knowledge in CAPP systems is of a heuristic and algorithmic nature due to experience being its source [9]. Heuristic methods enable the solution of planning problems, which cannot be solved with the aid of a formal mathematical apparatus. A broad review, together with the characteristics and classification of 52 CAPP systems categorised as expert systems and used in the 1990s is presented in [10]. In [7], the authors have also included a brief overview of knowledge representation diagrams in existent CAPP systems, formulated the requirements which should be met in this respect and have also proposed their own object-oriented model of knowledge representation.

Various methods of knowledge representation are used in CAPP systems, including: state space, predicate calculus, semantic nets [11], frames, production rules, object-oriented programming, decision tables [12] and decision trees. However, rule systems remain the most popular method of knowledge representation. In recent years, the greatest hopes for the most dynamic development of CAPP systems have been placed in such methodologies as: object knowledge representation [7, 13-15], neural networks [16], frames [17--19], hierarchical hybrid models of frames and rules [09] and the formalism of Petri nets [20-29].

Graphic knowledge representation occurs only rarely and until recently, all systems settled for the graphic visualisation of knowledge alone [30]. In order to be able to treat a database interface as a graphic interface, it is not enough to simply use standard tools of the GUI platform of the Windows operating system. Known cases usually relate to representation in the form of a simple tree graph or a flowchart, as seen in the example of the Strategy Manager module of the EdgeCAM system. Representation in the form of a flowchart works in the case of description of knowledge at a general level. However, flowcharts quickly expand with more detailed description, which makes their analysis and control more difficult and in effect, substantially hinders the creation of a cohesive knowledge base.

Employment of graphs in practical applications of manufacturing process planning is usually limited to presentation of certain relations in the designed process (operation) [31]. Attempts at constructing a graphic interface visualising Petri nets for the purposes of manufacturing process planning have so far been sporadic. One of such attempts has been presented in [25], where a Petri net is used for verification of the correctness of the generated production process plan. Another example of a graphic interface made available to the user for purposes of a cell production model has been described in [32]. Clearly, universal software exists which visualises the graphic form of standard Petri nets however these are difficult to adapt for CAPP and knowledge base needs.

The selection of machining operations is one of the most important tasks in process planning. The topic of drilling operation planning has been described in numerous papers, including [15, 18, 21, 23, 25, 33-37, 38-45].

## 2. Knowledge acquisition for CAPP

Transfer of knowledge occurs in the acquisition process from knowledge sources such as experienced machine design engineers plus construction and manufacturing documentation gathered over the years into a formalised form dependent on the accepted method of its representation in the expert system. Worthy of emphasis at this stage is the dynamic nature of knowledge about manufacturing processes, which results from the changing means of their execution (tools, machines) as well as the skills and knowledge of engineering personnel. The usual approach toward knowledge base development is to use knowledge acquisition techniques to elicit knowledge from an expert and represent it in the knowledge base. The cost and performance of the application depends directly on the quality of the knowledge acquired. The necessary capabilities of a knowledge-acquisition framework are the following: visualization and browsing existing knowledge, editing and reviewing knowledge, entering new knowledge, search and retrieval of specific parts of the knowledge base, plus control of acquisition dialogues and annotation. In terms of its structure, the knowledge acquisition module usually constitutes a separate module of the expert system although it can be integrated with the user interface [27].

The knowledge acquisition process is complex and in general, consists of a series of actions that include: problem recognition, conduct of preliminary interviews, acquisition of knowledge from knowledge sources, collection, analysis, modelling, validation of knowledge and its annotation in the form of formal representation or a decision model. The knowledge acquisition process does not usually end when it is entered into the knowledge base. Knowledge continues to be supplemented, verified and changed at the stage of use of the expert system. Knowledge sources firstly consist of experts and specialists in a given field as well as documented information sources (manuals, reports, standards, company catalogues, databases, notes and documentaries). The overall view prevails that the knowledge acquisition process constitutes the “bottleneck” in the construction of expert systems, and hence also CAPP systems based on expert systems. Knowledge acquisition is one of the most difficult, laborious and error-prone phases that a knowledge engineer carries out while building a knowledge-based system.

In last years, attempts have been made to gradually automate the knowledge acquisition process in order to make it more effective. One of the most promising methods in this scope is case-based reasoning method [8, 38, 46-48]. In [49] the authors propose a related method for application in rotating pieces. These methods, although based on a simple idea, are very laborious. Paper [50] presents a knowledge acquisition method based on the results of simulations performed with a special programming platform.

Various approaches to knowledge capture are possible. From the point of view of the degree of automation, knowledge acquisition methods for CAPP can be divided into four classes:

I. Manual acquisition through various forms of dialogue between the knowledge engineer and the expert - subject matter specialist.
II. Manual acquisition performed by the knowledge engineer on the basis of manufacturing documentation available in paper or electronic form.
III. Automatic acquisition on the basis of manufacturing documentation available in electronic form.
IV. Computer aided acquisition of knowledge of manufacturing processes performed directly by the specialists, designers of the manufacturing process.

Methods belonging to class I are traditional acquisition methods with all their disadvantages, i.e.: they require an experienced knowledge engineer, familiar with the issues of manufacturing processes; the consent and "good will" of machine design engineers; overcoming difficulties in the verbalisation of knowledge by manufacturing process designers. The following forms of dialogue between the knowledge engineer and the machine design engineer are used here:

- interviews (dialogue) with the experts;
- analysis of questionnaires filled out by the experts;
- analysis of reports prepared by the experts;
- observation of the experts at work.

Methods belonging to class II, like those of class I, require an experienced knowledge engineer with at least a general knowledge of the manufacturing techniques or the cooperation of machine design engineers. Here the preliminary interviews with the experts constitute one of the more important stages of the system's creation. The usability and functionality of the system are dependant from the quality of the interviews. This method is always very laborious and therefore expensive.

A prerequisite for applying class III methods of acquisition of manufacturing processes knowledge is the existence of a fairly complete, coherent, computer databases of manufacturing processes in the production plant. Only a minor fraction of enterprises in the machine industry currently meets this condition. Manufacturing processes in existing databases are incomplete and contain numerous errors, and the databases themselves are seldom adapted to being subjected to clustering and classification procedures. Seldom is there any connection between the design documentation (e.g. dimensions on manufacturing drawings) and the manufacturing documentation. Another prerequisite for applying this method is the existence of equipment, manufacturing tooling and machinery stock databases which complement the manufacturing processes. Even if these obstacles are overcome, another problem arises - the adaptation of the methods used for extracting the data needed to formulate the rules in the knowledge base. In practice a major part of the appropriate software has to be developed from scratch. Therefore class III knowledge acquisition methods, although the most attractive, at present have little chances of implementation in manufacturing practice.

In methods belonging to the last class, class IV, the data acquisition process is not fully automated. Neither is the knowledge engineer directly involved in the realization stage of the data acquisition process. In practice however, the latter proves to be a large advantage. It is the designer of the manufacturing process himself, who during subsequent interactions decides about the data to be stored every time. Through a customized interface he has the possibility to control and verify the rules entered into the system at all times. He does not have to rely on the presence of the knowledge engineer in the process, so he may do it at the moment most convenient to himself. Only knowledge acquired in this way can produce the feeling of full authorization and reliability. Such an individual approach is possible in many technology labs in various companies at the same time basing on the same knowledge acquisition mechanisms. Therefore appropriate software may have very universal features, although knowledge acquired in this way may be very flexible and individualized. This is the knowledge acquisition method used in the approach proposed in this article.

In practice it often happens that the knowledge comes from several different sources or is stored in different forms during the first stage and it is necessary to standardize and integrate it. This problem is presented below in diagrammatical form (Fig. 1). Such cases, inevitable now and then, greatly increase the difficulty in constructing a CAPP system. To reduce the difficulty it is necessary to standardize the data representation method already at the acquisition stage [51].

In scientific research aimed at the automation of the data acquisition process, use is most often made of induction algorithms (e.g. ID3 [52] or AQ11 [53]) capable of producing general decision rules on the basis of a learning set, i.e. a set of examples of single choices. These sets, expressed in the form of learning files, most often contain archived data describing the problem situation and the conclusion of the human resulting from it. On the basis of this data the system learns to solve similar problems on its own. In expert systems the knowledge may be distributed between several files, called knowledge sources.

Each of the knowledge sources can then store knowledge necessary for the solution of another sub-problem. In order to verify the hypotheses formulated in the initial stage, Randomised Controlled Trials (RTC) are carried out in subsequent stages. Another way of automating the acquisition process are textual analysis programs, but their usefulness in the subject domain of machine building technology is doubtful.

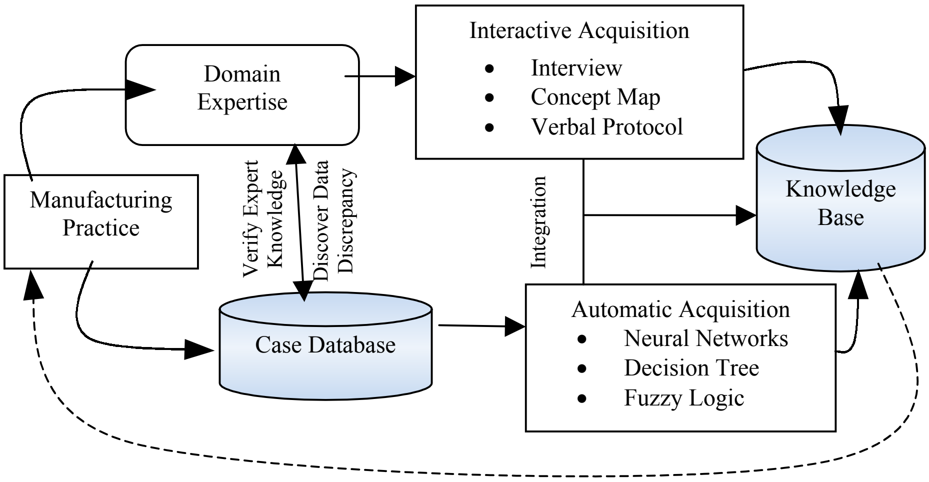


Fig. 1. The integrated knowledge acquisition methodology [51]

The issue of knowledge acquisition – implicit, hidden, originating from the intuition and experience of the engineers designing the manufacturing process – by means of data mining in an intelligent database was presented in [54]. An intelligent database was defined as a hybrid system consisting of a relational database, a knowledge base, a knowledge acquisition module, a user interface, an expert system and a neural network. The engineer, using the intelligent database, designs the process according to the semi-generative method. Ready-made knowledge engineering tools were used to construct the intelligent database: the Sphinx package, the CAKE program, the PC-Shell expert system shell and the Neuronix – artificial neural networks simulator. Classification, being one of the sub-tasks of pattern recognition, was chosen as the data mining method in the intelligent knowledge base. In this way a software platform capable of realising selected sub-tasks in the CAPP system, was obtained.

The learning and adaptation abilities are the main features of the artificial neural networks which determine their high effectiveness in the knowledge acquisition process [55]. Most probably, the first work to use ANN in the process of acquiring knowledge of manufacturing processes was [56]. In [57] an unsupervised learning algorithm, generating the order of setups and EFO machining sequences was presented. The author pointed out the necessity of taking into account the tolerance of dimensions between features, the type of material and machining operations. The problem of tolerance of dimensions between features was first solved only in [58], where a neural network for the automation of designing the machining of rotating equipment.

The works [51, 59, 60] raise the issues of automatic knowledge acquisition in the fields of design and manufacturing with the use of fuzzy linguistic terms. A two layer neural network was used for this purpose (input layer and output layer), which greatly reduces the rank of complexity of the obtained rules, since it only allows a linear separation of problems. Nevertheless, the results obtained still surpassed those of the traditional approach, consisting in constructing an abstract mathematical model by means of regression analysis. This method is deeply inspired by the analysis of the behaviour of engineers working on manufacturing processes. The benefits from the proposed approach are worthy of attention, and from the point of view of the authors the most important of them are that:

- "information noise" is tolerated in the analysed data;
- unlike regression analysis, an initial choice of a mathematical model is not required;
- the rules supplied are intuitive and simple, easily understandable by the user.

A detailed comparison of the features and possibilities of neural networks in the construction of expert system together with a comprehensive biography on the subject can be found in the works [55, 61].

## 3. Petri nets in CAPP

The interest in Petri net methodology for the purpose of designing manufacturing processes appeared in the second half of the 1980 s. The potential possibilities offered by the use of Petri net methodology in designing discrete production processes have been indicated in [62]. A work which deserves mention as one of the most important achievements of that period is [17], where a Petri net was used for controlling the flow of information. The inventiveness of this approach consisted mainly in the use of Object/Operation (O/O) dualism, which manifested itself in a uniform representation (in the form of frames) of these two components of the model.

The first attempts to use Petri nets in designing manufacturing processes were concerned with linking the plan of the manufacturing process to the conditions resulting from the potential of the manufacturing department. What is worth noticing is the proposition to use (in real-time) the data from the Petri net model controlling the course of production for the verification of the manufacturing process being designed. Thus a prototype of a dynamic CAPP system was born [26]. Another team focused their research on the analysis of possibilities of scheduling operations in the manufacturing process and the representation of alternative courses of the manufacturing process on the basis of a Petri net model [63]. At the same time Lee and Jung [23] predicted the use of Petri nets modelling knowledge related to the selection and scheduling of operations and an elastic representation of the ordering of the operations. The most comprehensive approach in the 1990s was presented in [24]. It included both the acquisition of knowledge and the modelling of the structure of the process as well the evaluation of the generated Petri net. The aim of the authors was to construct a knowledge-based methodology of modelling the manufacturing process.

The idea of using bipartite graphs, which Petri nets are in their graphical representation, for modelling chronological structure first appeared in Polish scientific literature in [64]. The author observed that "normal graphs" can only model relations between processing operations, while in designing and analysis of the processes there exist important structural characteristics which should be reflected in the formal description of the structure of the process as for example the dependencies resulting from the selection of processing bases. Therefore the author introduced two types of arcs-relations, traditional arcs representing the ordering relation and additional arcs indicating the base to processed surface relation.

The overview of the uses of Petri nets in designing manufacturing processes up to 1992 is presented in [20]. After this period a number of significant applications of Petri nets in manufacturing processes modelling were developed. In the opinion of the author those deserving particular attention are the works of Dimitris Kiritsis from the Swiss Federal Institute of Technology in Lausanne, the series of works of Dusan N. Sormaz from the University of Ohio, the research conducted on the Technical University of Milan [21] and the University of Pohang (Korea) [23].

The most extensive project in the area of modelling and analysis of manufacturing processes with the use of the Petri net apparatus is the development of the Process Specification Language - PSL [22]. Work on this project, coordinated by the National Institute of Standards and Technology (NIST) has continued for over a dozen years. Its aim is to draw up an international standard of a language for the description of all aspects of the realization of the manufacturing process. Before defining this language a thorough analysis of the earlier achievements in this area was made [65]. The technical representation of the PSL conception for manufacturing process designing is a class of Petri nets called CPP-net (Compact Process Planning net).

## 4. Knowledge representation by Petri nets

Usually, publications concerning expert systems or, more broadly speaking, knowledge-based systems do not mention the possibility of representing knowledge by means of the Petri net apparatus, while as already demonstrated in several publications, the Petri net apparatus is a ready knowledge carrier with many potential possibilities of enriching it, competitive to the currently most popular rule-based systems [22, 66-70]. Table 1 presents the corresponding components of the rule-based approach to knowledge representation and the Petri net-based approach.

In the second half of the 1980 s [70] research aimed at creating a structural formalization of the representation of knowledge based on the Petri net apparatus was taken up. One of the results of this research is the methodology of Logical Petri Nets (LPN), enabling easy modelling and verification of knowledge. Basing on the transformation of rules in a knowledge base to equivalent Petri nets, Zaidi [67] uses the structural properties of Petri nets for the detection of errors in the knowledge base. [69] presents a fuzzy inference algorithm and a backward propagation algorithm for an Adaptive Fuzzy Petri Net (AFPN).

Tab. 1. Correspondence between the rule-based approach and the Petri net approach [23]

| Attribute | Rule-based approach | Petri net-based approach |
|---|---|---|
| Event (or Operation) | Rule | Transition |
| Cause | Antecedents | Input places |
| Effect | Consequents | Output places |
| Overall structure | Rule base | Complete net |
| Object | Fact | Token |
| State | Fact base | Marking Vector |
| Evaluation | Inference engine | Transition firing |
| Uncertainty | Certainty factor | Probabilistic arc |
| Global information | Fact base | Global data |
| Dynamic information | Working memory | Marked places |

## 5. GTX – shell system for CAPP

The first significant attempt to create a CAPP-oriented programming platform with the features of an expert system shell was made at the University of Illinois in the first half of the 1990 s [71]. A platform named PPEP (Process Planning Enabled Platform) built there enables the description of the geometry of the designed part in the form of a set of basic geometric entities and tolerances, the selection of the (partially ordered) manufacturing process, the selection of machines, settings, the specification of operations and the generation of documentation. The resulting platform was a major step towards the development of CAPP systems. Graphical tools for the representation of the chronological structure of the operations appear very rarely. An example of a prototype graphical interface undergoing tests was presented in [72]. In systems involving the management of a knowledge base for CAPP purposes, graphics is only used as a passive tool for the visualisation of the facts and rules entered e.g. on the basis of data saved in the XML format [43]. Graphics is not used as an active tool for such purposes.

The representation of knowledge in the GTX system is based on the binary Petri net class with inhibitor arcs in the form of an ordered six:

$$PN = (P, T, E, F, I, M_0)$$

where: $P$ is a non-empty, finite set of places, $T$ is a non-empty, finite set of transitions, disjoint with $P$, $P \cap T = 0$, $P \cup T \neq 0$, $E \subseteq (P\ 3\ T) \cup (T\ 3\ P)$ is the incidence relation (the set of pt and tp arcs), $F$ is the set of information arcs (the marker does not flow through the arcs of the type p_t), $I$ is the set of inhibitor arcs, $M_0$: $P \to \{0,1\}$ is the function of initial marking.

$M$ is in fact a unit vector with $|P|$ components, where the components which are equal to 1 correspond to the places where the marker is located. The flow conditions of a so defined Petri net are presented on Fig. 2. In other marking cases the transition is impossible. So defined a class of Petri networks has the features of a logical Petri network. The use of Boolean operators (AND, NOT, OR) is not necessary since it is possible to realise them with the structure of the net itself.

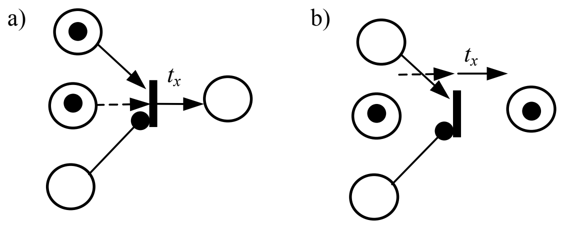


Fig. 2. The conditions for the firing of the transition $t_x$: a) marking before the transition is fired, b) marking after the transition is fired

Apart from active graphic functions, enabling the creation of a two-dimensional drawing of the Petri net, the approach proposed in the GTX system includes the possibility of placing raster images illustrating the modelled objects in the background of the Petri net. This allows the user to quickly localise the appropriate fragment of the knowledge base and to quickly browse its contents without going into details of the rules. The project guidelines were to create a knowledge base managed independently by the direct user of the computer program - the manufacturing process engineer of machine design, unskilled in the methodology of knowledge acquisition and processing. The manner of presentation of the knowledge is easy, clear and user-friendly. The formal side of the knowledge representation apparatus is, on the other hand, as hidden as possible.

GTX enables the acquisition of knowledge, its presentation, verification, processing and storage by means of a text (Fig. 3) and graphical (Fig. 4) user interfaces. The mechanism of knowledge processing, constituting the core of the integrated knowledge platform, is the common part (common source code) of the GTX module and the GT program serving as a data transfer module. Both the GTX and GT modules use a knowledge base stored in alphanumeric (ANSI) form, which allows the user real-time access to it, also in edit mode (Fig. 3). This makes it very easy to operate o large blocks of text, to copy or delete entire fragments of knowledge and to quickly search the requested knowledge fragments.

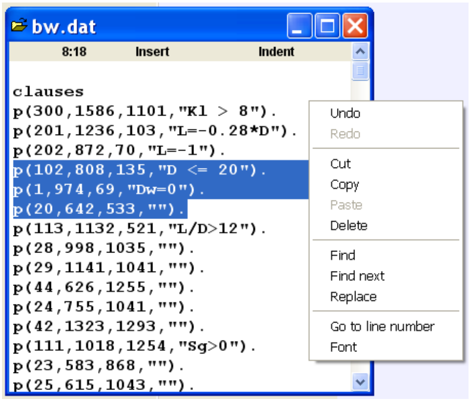


Fig. 3. Textual editor for knowledge base

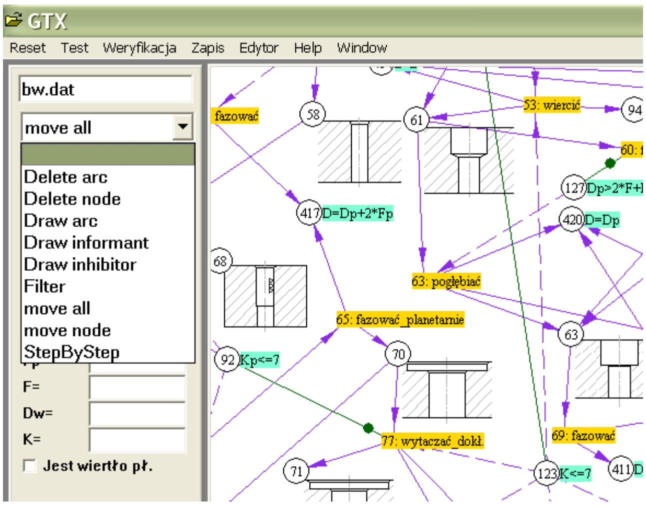


Fig. 4. Part of canvas of graphical knowledge editor

The prototype of the presented knowledge acquisition platform is currently undergoing tests in production conditions. The prerequisite for the effective application of such a solution is the provision of a uniform system of variable parameters describing the particular features (Fig. 5), common for the CAD and the CAPP.

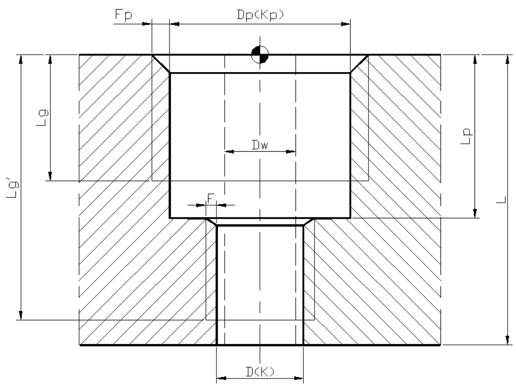


Fig. 5. Parametric machining features

Figure 6 presents the general structure of the GTX integrated knowledge transfer platform and the main data streams used for knowledge transfer.

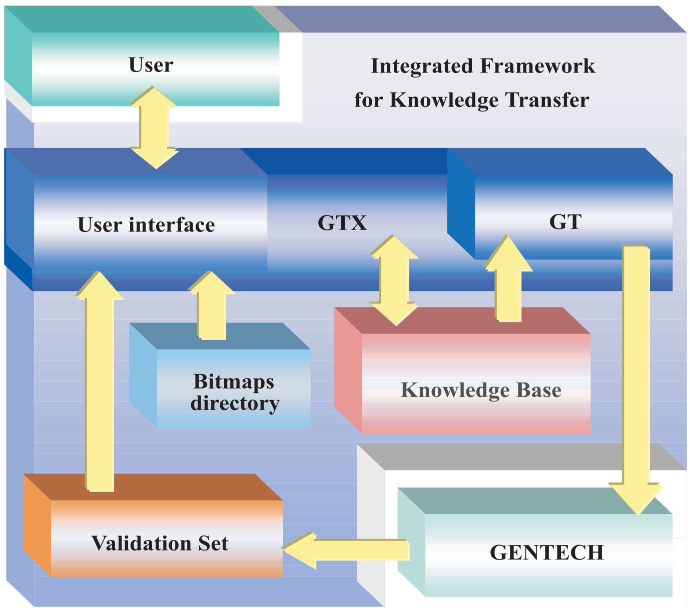


Fig. 6. General structure of the integrated framework for knowledge transfer

## 6. Conclusion

This paper presented a knowledge-based approach to hole-machining process selection. A Petri net-based graphical interface was incorporated in the knowledge framework. This user-friendly framework enables the engineer to successfully extract, apply and validate knowledge. It provides an interface supporting effective interaction by facilitating input, producing output and reports in flexible formats as well as displaying results in graphic form. It offers a structured knowledge representation in the form of rules and an explicit inference route and therefore possesses the capability of explanation facility.

### References


[1] H.C. ZHANG, L. ALTING: Computerized manufacturing process planning systems. Chapman and Hall, London 1994.

[2] X. ZHOU, Y. QIU, G. HUA, H. WANG, X. RUAN: A feasible approach to the integration of CAD and CAPP. *Computer-Aided Design*, **39**(2007), 324-338.

[3] I. KURIC, S. LEGUTKO: Chosen aspects of modern CAPP systems. *Computational Methods in Science and Technology*, **7**(2001)2, 65-74.

[4] R. KNOSALA: Zastosowanie metod sztucznej inteligencji w inżynierii produkcji. WNT, Warszawa 2002.

[5] U. BOSE: A cooperative problem solving framework for computer-aided process planning. Proc. 32nd Hawaii Inter. Conf. on System Sciences, Maui 1999.

[6] K. WANG: An integrated intelligent process planning system for machining. *J. Intelligent Manufacturing*, **9**(1998), 503-514.

[7] D.N. SORMAZ, B. KHOSHNEVIS: Process planning knowledge representation using an object-oriented data model. *J. CIM*, **10**(2000)1, 92-104.

[8] J. POKOJSKI: Systemy doradcze w projektowaniu maszyn. WNT, Warszawa 2005.

[9] J. DUDA, J. POBOŻNIAK: Hierarchiczny model wiedzy technologicznej. Mat. konf. „Podstawy Projektowania Procesów i Systemów Produkcyjnych", Politechnika Krakowska, Monografia **150**(1993), 51-61.

[10] D. KIRITSIS: A review of knowledge-based expert systems for process planning. Methods and problems. *J. Advanced Manufacturing Technology*, **10**(1995), 240-262.

[11] Y. HAO: Research on auto-reasoning process planning using a knowledge based semantic net. *Knowledge-Based Systems*, **19**(2006), 755-764.

[12] S. HALBE, P. NIRGUDKAR, K. UMAPATHY: Computer-aided process planning (CAPP) system with alternative process plans. Project for the Course IE550 – Manufacturing Systems, 2000.

[13] C. GRABOWIK, K. KALINOWSKI, Z. MONICA: Integration of the CAD/CAPP/PPC systems. *J. Materials Processing Tech.*, **164**(205), 1358-1368.

[14] J. HABEL: Obiektowo-hierarchiczna reprezentacja procesu technologicznego dla potrzeb systemu CAPP. Mat. konf. „Metody i Środki Projektowania Wspomagane Komputerowo", Kazimierz Dolny 2005, 133-140.

[15] A. CHEP, L. TRICARICO, P. BOURDET, L. GALANTUCCIO: Design of object-oriented database for the definition of machining operation sequences of 3D workpieces. *Computer Industrial Engineering*, **34**(1998)2, 257-279.
[16] S.H. HUANG, H.C. ZHANG: Artificial neural networks in manufacturing: concepts, applications and perspectives. *IEEE Transactions on Components, Packing and Manufacturing Technology*, **17**(1994)2, 212-228.
[17] M. FURUKAWA, Y. KAKAZU, N. OKINO: Control of design process with Petri net for CAD-knowledge representation based object/operation dualism. *J. of the Japan Society of Precision Engineering*, **5**(1989)55, 877-882.
[18] G. DEVEDŽIĆ: A knowledge based system for drilling and milling cutting tools selection. G*épgyártástechnológia*, **11**(1992).
[19] J. DUDA, J. HABEL, J. POBOŻNIAK: Semi-generative CAPP system. *WEB Journal: CA Systems in Production Process Planning*, 2002.
[20] J.A. CECILE, K. SRIHARI, C.R. EMERSON.: A review of Petri net application in process planning. *J. Advanced Manufacturing Technology*, **7**(1992), 168-177.
[21] B.M. COLOSIMO, Q. SEMERARO, T. TOLIO: Rule based system for non linear process plan generation. *Studies in Informatics Control*, **9**(200)2, 133-143.
[22] D. KIRITSIS, P. XIROUCHAKIS, C. GUNTHER: Petri net representation for the process specification language – Part 1: Manufacture process planning. Proc. Conf. Inter. "Workshop on Intelligent Manufacturing Systems IMS-EUROPE", Lausanne 1998.
[23] K.H. LEE, M.Y. JUNG: Flexible process sequencing using Petri net theory. *Computers and Industrial Engineering*, **28**(1995) 2, 279-290.
[24] I.J. RUDAS, L. HORVÁT: Modelling of manufacturing processes using a Petri-net representation. *Engineering Applications of A. I.*, **10**(1997)3, 243-255.
[25] D.N. SORMAZ, S. THIRUPPALLI, J. ARUMUGAM: Evaluation of manufacturing feature precedence constraints using Petri nets. Proc. 11th Industrial Engineering Research Conf., Orlando 2002.
[26] K. SRIHARI, C.R. EMERSON: Petri nets in dynamic process planning. Proc. 12th Annual Conf. on Computers and Industrial Engineering, Orlando 1990, 447-451.
[27] R. STRYCZEK: Wizualny interfejs użytkownik-baza wiedzy. Mat. konf. „Inżynieria Wiedzy i Systemy Ekspertowe", Wrocław, **2**(2006), 93-102.
[28] R.R. WU, L. MA, J. MATHEW, G.H. DUAN: Optimal operation planning using fuzzy Petri nets with resource constraints. *J. CIM*, **15**(2002)1, 28-36.
[29] X.F. ZHA, S.Y.E. LIM, W.F. LU.: A knowledge intensive multi-agent system for cooperative/collaborative assembly modeling and process planning. *J. Integrated Design and Process Science*, 2003, 99-122.
[30] Z. KULPA, M. SOBOLEWSKI: Knowledge-directed graphical and natural language, interface with knowledge-based concurrent engineering environment. Report CERC-Tr-Tm-92-001, West Virginia University, Morgatown 1992.
[31] G. BRITTON, G. THIMM, T.S. BENG, F. JIANG: A graph representation scheme for process planning of machined parts. *J. Advanced Manufacturing Technology,* **20**(2002), 429-438.
[32] K. CHENG, J. POPOV: Internet-enabled modeling of extended manufacturing enterprises using process-based technique. *J. Advanced Manufacturing Technology*, **23**(2004), 148-153.

[33] J. DETAND, J.K. KRUTH, H. THIELEMANS: COMPLAN Process planning approaches. www.mech.kuleuven.ac.be/pma/project/complan/appcpp.html.

[34] B. KHOSHNEVIS, W. TAN: Automated process planning for hole-making, *American Society of Mechanical Engineers, Manufacturing Review*, **8**(1995)2.

[35] K.P. NEUENDORF, D. KIRITSIS: Operation sequencing for optimal process planning using Petri net based methods. *Informatik-Bericht*, **85**(1997)4.

[36] D.N. SORMAZ, B. KHOSHNEVIS: Intelligent process planning implemented as an integrated module of CIM. Proc. ASME Design Engineering Technical Conf., Sacramento 1997.

[37] D.N. SORMAZ, B. KHOSNEVIS: Generation of alternative process plans in integrated manufacturing systems. *J. Intel. Manufacturing*, **14**(2003), 509-526.

[38] M.K. TIWARI, K. RAMA KOTAIAH, S. BHATNAGAR: A case-based computer-aided process-planning system for machining prismatic components. *J. Advanced Manufacturing Technology*, **17**(2001), 400-411.

[39] D.H. LEE, D. KIRITSIS, P. XIROUCHAKIS: Operation sequencing in nonlinear planning: local search heuristic. *Studies in Informatics and Control J.*, **11**(2002)1.

[40] M. SADAIAH, D.R. YADAV, P.V. MOHANRAM, P. RADHAKRISHAN: A generative computer-aided process planning system for prismatic components. *J. Advanced Manufacturing Technology*, **20**(2002), 709-719.

[41] S.S. PARK, G. MUKUNDAN, S. GU, G.J. OLLING: In-process model generation for the process planning of a prismatic part. *J. Advanced Manufacturing Systems*, **2**(2003)2, 147-162.

[42] T.N. WONG, C.F. CHAN, H.C.W. LAU: Machining process sequencing with fuzzy expert system and genetic algorithms. *Engineering with Computers*, **19**(2003), 191-202.

[43] A. WADATKAR: Process selection for hole operations using rule based approach. Thesis, Ohio University, Athens 2004.

[44] H. YONGTAO, M. JINGYING: A knowledge-based auto-reasoning methodology in hole-machining process planning. *Computers in Industry*, **57**(2006), 297-304.

[45] S. YAO, X. HAN, Y. YANG, Y. RONG, S.H. HUANG, D.W. YEN., G. ZHANG: Computer-aided manufacturing planning for mass customization: part 1, framework. *J. Manufacturing Technology*, **32**(2007), 194-217.

[46] S. CHAMPATI, W.F. LU, A.C. LIN*:* Automated operation sequencing in intelligent process planning*: A* case-based reasoning approach. *J. Advanced Manufacturing Technology*, **12**(1996), 21-36.

[47] J. VÁNCZA: Planning in manufacturing domains controlled by case-reasoning. Proc. AAAI-98 Workshop, Madison 1998, 161-165.

[48] C.F. YUEN, S.Y. WONG, P.K. VENUVINOD: Development of a generic computer-aided process planning support system. *J. Materials Processing Technology*, **139**(2003), 394-401.

[49] F. SCHMALHOFER, R. BERGMANN, O. KUHN, G. SCHMIDT: Using integrated knowledge acquisition to prepare sophisticated expert plans for their re-use in novel situations. Research Report PP-92-25, German Research Center for AI, Kaiserslautern 1992.

[50] X. SHI, J. CHEN, H. YANG, Y. PENG, X. RUAN: A novel approach to extract knowledge from simulation results. *J. Advanced Manufacturing Technology*, **20**(2002), 390-396.

[51] H. XING, S.H. HUANG, J. SHI: Rapid development of knowledge-based systems via integrated knowledge acquisition. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **17**(2003), 221-234.
[52] J.R. QUINLAN: Semi-autonomus acqisition of pattern-based knowledge. *Introductory Readings in Expert Systems*, **12**(1982).
[53] R.S. MICHALSKI, E.L. CHILAUSKY: Knowledge acquisition by encoding expert rules versus computer induction from examples. *J. Man-Machines Studies*, **12**(1980), 63-87.
[54] I. ROJEK-MIKOŁAJCZAK, Z. WEISS: Sztuczna inteligencja w procesach technologicznych. *CADCAM Forum*, **10**(2001), 40-46.
[55] H.C. ZHANG, S.H. HUANG: Applications of neural networks in manufacturing: A state-of-the-art survey. *J. Production Research*, **33**(1995)3, 705-728.
[56] G.M. KNAPP, H.P. WANG: Acquiring, storing and utilizing process planning knowledge using neural networks. *J. Intel. Manufacturing*, **3**(1992)5, 333-344.
[57] C.L.P. CHEN: Setup generation and feature sequencing using unsupervised learning algorithm. Proc. Design and Manufacturing Systems Conf., Dearborn 1993, 981-986.
[58] J. MEI, H.C. ZHANG, W. OLDHAM: A neural network approach for datum selection in CAPP. *Computers in Industry*, **27**(1995), 63-87.
[59] S.H. HUANG, X. HAO, M. BENJAMIN: Automated knowledge acquisition for design and manufacturing: The case of micromachined Atomizer. *J. Intelligent Manufacturing*, **12**(2001), 377-391.
[60] S.H. HUANG, H. XING: Extract intelligible and concise fuzzy rules from neural networks. *Fuzzy Sets and Systems*, **132**(2002), 233-243.
[61] S.H. HUANG, H.C. ZHANG: Neural-hybrid approach for intelligent manufacturing: A survey. *Computer and Industry*, **26**(1995), 107-126.
[62] I. HAM, C.Y. LU: Computer-aided process planning: The present and the future. *Annals of the CIRP*, **37**(1988), 1-11.
[63] D. KIRITSIS, M. PORCHET, A. BELHI: A generic Petri net model for dynamic process planning. Proc. ASME Int. Computers and Engineering Conf., Mineapolis 1994, 235-242.
[64] J. SZADKOWSKI: Formalny opis struktury procesu technologicznego. Mat. konf. „Podstawy Projektowania Procesów i Systemów Produkcyjnych", Kraków 1993, 229-236.
[65] A. KNUTILLA, T. POLYAK, C. SCHLENOFF, A. TATE, S.CH. CHEAH, S. RAY, ANDERSON R.C.: Process specification language: Analysis of existing representations. NISTIR 6133, National Standards and Tech., Gaithersburg 1998.
[66] M.L. GARG, S.I. AHSON, P.V. GUPTA: A fuzzy Petri net for knowledge representation and reasoning. *Information Processing Letters*, **39**(1991), 165-171.
[67] A.K. ZAIDI: Validation and verification of decision making rules. Technical Report GMU/C31-155-TH, George Mason University, Fairfax 1994.
[68] S.J.H. YANG, W.C. CHU, J. LEE, W.T. HUANG: A fuzzy Petri net mechanism for fuzzy rules reasoning. Proc. 21th Conf. Computer Software and Application, Washington 1997, 438-443.

[69] X. LI, W. YU, F. LARA-ROSANO: Dynamic knowledge interface and learning under adaptive fuzzy Petri net framework. *IEEE Transactions on Systems Man and Cybernetics*, **30**(2000)4, 442-450.
[70] C. JIANG, Y. ZHENG: Fuzzy reasoning based on Petri nets. *Studies in Informatics and Control*, **9**(2000)3, 195-206.
[71] V. HETEM, K. CARR, M. LUCENTI, O. RUIZ, X. ZHU, P.M. FERREIRA, C.Y. LU: Specification for a process planning enabling platform. *J. Systems Engineering*, **5**(1995), 48-59.
[72] J.D. SUMMERS, B. BETTIG, J.J. SHAH: The design exemplar: A new data structure for embodiment design automation. *J. Mechanical Design*, **126**(2004), 775-787.

*Received in February 2008*