Manufacturing Process Modeling Method for CAD/CAM and Flexible Manufacturing Systems

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Abstract

Knowledge based automation of the manufacturing process planning is an evergreen problem area of integrated design and planning (CAD/CAM) systems as well as flexible manufacturing systems (FMS). The authors propose a Petri net and rule based modeling method for manufacturing process planning. The generic nature of this model makes it possible to handle all of the process variants. The model is then evaluated by process planning and production scheduling procedures. Models are created on the basis of data of form features oriented part model and manufacturing environment. Petri net objects are created using manufacturing process objects and process structure information. The paper is organized as follows: First the aims of the research are outlined and the characteristics of manufacturing process models of this type are summarized. Next, the method of modeling, the structure of the process model and the process model entities are detailed. Following this, a generation procedure of the process model is presented. Finally, an example of process model is explained.

Keywords

Modeling of Manufacturing Processes, Petri Net Model, Knowledge Based Generation of Model Entities, Generation of Petri Nets.

1. INTRODUCTION

Flexible generation of manufacturing process plans is a main concern in both CAD/CAM and flexible manufacturing systems (FMSs). Integrated product modeling concepts stimulate research in this field. Important result of product modeling efforts in the last decade is the STEP (Standard for Exchange of Product Model Data, ISO 10303). In this work the product model approach of the STEP has been taken into consideration. It is well-known that decision intensive nature of manufacturing process planning calls for knowledge based methods. A product model consists of partial models. One of the problematic partial model within product models is the manufacturing process model (Eversheim, W. and Marcziński, G. and Cremer, R., 1991). Methods for creation of model entities are in the center of development work at present day computer aided design and planning systems. Future systems demand knowledge based procedures for creation and evaluation of manufacturing process models. Conventional knowledge based methods for modeling applied at computer aided manufacturing process planning have not enough to fulfill the requirements of present day CAD/CAM and flexible manufacturing systems.

The paper is organized as follows. First the aims of the research are outlined and the characteristics of manufacturing process models of this type are summarized. Next, the method of modeling, the structure of the process model and the process model entities are detailed. Following this, a generation procedure of the process model is presented. Finally, an example of process model is explained. The work presented in this paper has been restricted to modeling of manufacturing processes of mechanical parts.

2. MODELING OF MECHANICAL PARTS

Comprehensive range of methods and tools for shape modeling, form feature modeling, finite element analysis, tool path generation and other tasks are available in these days for engineers. Manufacturing process modeling has been placed into other engineering modeling activities and the correct functional and data communication connections have been revealed. This was the basis of the process modeling research that made by the authors. They made proposal for manufacturing process model structure, Petri net representation for process model entities and application of knowledge based paradigms to process modeling (Horváth, L. and Rudas, I. J., 1994, 1995). The effects of human-computer procedures on design and planning work have been analyzed (Horváth, L. and Rudas, I. J., 1994/2).

Figure 1 shows product modeling activities that are in relation with manufacturing process modeling. Main classes of these activities are modeling by geometric, engineering (H. Grabowski and R. Anderi and M. J. Pratt, 1991), and manufacturing objects of the part. Communication between computer programs and humans greatly affects these modeling activities. Manufacturing of mechanical parts is characterized by less or more number of

suitable process variants taking into account a given manufacturing capacity. The process model must contain information on all available process variants. This gives flexibility for production scheduling. Entities that are involved in the proposed manufacturing process model carry information for all suitable variants of a process or a process element for a cluster of manufacturing tasks. At the same time model entities carry knowledge to select the most suitable variant. Because both conditions in the manufacturing environment and the production schedule are subjected to changes in the every day industrial practice, the manufacturing process must be modified frequently. This can be done by re-evaluation of the proposed generic process model. Application of advanced form feature based shape modeling techniques are assumed at the product model.

Figure 1 Modeling of products.

3. FOUR LEVELED MANUFACTURING PROCESS MODEL

Activities for development of advanced modeling methods in these days involve implementation of the concept of application oriented features. Models are built by features or features are recognized in models. The authors made an attempt to elaborate a feature based method for manufacturing process modeling (Horváth, L. and Rudas, I. J., 1994, 1995). Manufacturing process feature is any element of a manufacturing process that helps to understand a manufacturing related to a part, a form feature, a machine tool, or a cutting tool. Model entities are instances of manufacturing process feature classes. The feature instances have generic characteristics. The feature class is a global term whereas feature instance is for a given machining task and manufacturing environment. Feature libraries may contain features and their instances as usual in object oriented computer aided design and planning systems.

The authors have proposed a four leveled model in which model features are placed at the process (L1), setups (L2), operations (L3) and numerical control (NC) cycles (L4) level as it

can be seen at Figure 2. Model features are processes, net of setups, net of operations and sequence of cycles. Nets of operations are for setups and manufacturing of form features. On the level 1 process variants are mapped for manufacturing of the part. Level 2 involves process features that describe all possible sets of setups. A setup is part of the manufacturing process that is done using a single machine tool with the same clamping position. Level 3 contains possible sets of operations. Operation is a manufacturing that is realized using the same cutting tool. Level 4 is for tool cycle sequences.

Figure 2 Levels and features in the process model

There are process features that have a net structure. These are net of setups and net of operations process features. Elements of the structure are setup or operation manufacturing process objects and have attributes. The actual state of the process feature represents a sequence of setups or operations. The actual state is generated in course of evaluation of the net using built-in knowledge. The actual state is changed by repeated evaluation process taking

into account modified initial conditions. Repeated evaluation is initiated by an appropriate procedure or an engineer on the basis of changes in product data, production environment data or preferences for production scheduling. In common sense the process entity offers a manufacturing process or subprocess that is changeable according to the changing requirements. That is an important characteristic of the proposed process model that makes it suitable for application at flexible manufacturing systems.

After an assessment on the nature of modeling task and the needed computing power, implementation of ordinary marked Petri net formalism with some extensions had been decided. These Petri nets consist of places and transitions (Figure 3.). Transitions represent setup or operation process object. Description of process object by their attributes is attached to the transition. Special transitions represent AND and OR splits and joins similarly as proposed in (Kruth, J. P. and Detand, J, 1992). These transitions are used for creating branches. Place carries marking and identification of rules for selection the subsequent transition. Rules are placed in the knowledge base. Transition can have *in-process* or *out-process* status. In-process status of a transition represents process object that is in the actual process. Process objects that are represented by out-process transitions are not in the actual process but those transitions may gain in-process status after a new evaluation procedure.

Figure 3 Petri net representation

Marking of the Petri net is configured on the basis of suitability of process objects represented by transitions for the part manufacturing task. Evaluation starts on the first level of the model and advances level by level. Selection of process objects on the present level determines process features to be evaluated on the succeeding level. The evaluation procedure always is going on a given Petri net representation. The evaluation of a process model feature basically consists of two stages, namely checking the process objects involved and execution of

the Petri net. There is an initial marking of the Petri net. Previous to firing a transition the availability and suitability of the process object are checked and values its attributes are calculated using rules and equations. If a process object is not suitable, the marking is changed to make the transition disabled for firing. OR splits are used for making branches that represent variants. A branch is inactive if its first transition is disabled. If the execution of the net can not be continued because of the lack of enabled transition, the decision on the branch is revised. If checking of a process object leads to halt of the execution of the net, the process feature is not suitable for the manufacturing task. The process objects represented by the fired transitions are the actual ones. The model is evaluated from the point of view of both process planning and process scheduling. The extra features of the Petri net used here are:

- Special transitions for creating branch (AND, OR).
- Attaching rules to a place and a transition to make a validation of process objects possible previous to firing of the transition.
- Active and passive tokens. Token at a place becomes passive when a process object represented by the following transition is not suitable for the manufacturing task. Passive tokens are not taken into consideration at execution of the Petri net.
- Making it possible to use the Petri net model during both process planning and production scheduling.

If a transition is enabled, the token is moved in the usual way to the place that follows the fired transition. Value of status of the transition is changed from the *out-process* default value to *in-process*. If a transition is not enabled, the value of its status is *out-process*. At production scheduling, repeated evaluation of the process model so creating new process plan variant can be initiated. AND splits take it possible to fire all subsequent places. In this case all branches must be valid.

Repeated evaluation may be needed after any changes of manufacturing task description. Task description for the process planning involves data for

- class of part and form features,
- attribute values of part and form features,
- capabilities of manufacturing processes,
- available equipment and tooling and
- preliminary decisions on manufacturing process.

Petri net representations are interconnected within the generic process model but they are not synthesized into a complex net. Consequently, not only evaluation but also change of process features may take place. This characteristic gives flexibility for the modeling.

Other important and keenly researched application of Petri net is modeling and analysis of manufacturing systems (A. A. Desrochers and R. Y. Al-Jaar, 1995). These models can be interconnected with manufacturing process models in the future.

4. GENERATION OF PROCESS MODEL ENTITIES

The authors aimed to develop procedures for creating process model entities in a generative way using feature structure description and rule sets stored in a data base. This knowledge contains description of process feature classes, knowledge for selection of feature classes and knowledge for evaluation of process model entities. Generation of Petri net model representations can be followed on Figure 4.

Accuracy of description of manufacturing task is very important. On the basis of task description manufacturing process classes are selected. Classification tree gives class for given values of task parameters. Individual rules are applied where trees do not give solution. The next step is creation of basic process feature structure. Structure description is used and attributes are attached to manufacturing process objects that are involved in the structure.

Figure 4 Generation of Petri net model representations

Figure 5(a) shows process structure with nine manufacturing process objects (Mo1-Mo9). As an example, in this description Mo1-Mo9 process objects can be for center drilling (Mo1), drilling with two stepped twist drill (Mo2), drilling (Mo3), Boring (Mo4), drilling with two stepped precise drilling tool (Mo5), reaming (Mo6 and Mo7), counterboring (Mo8) and deburring (Mo9). A possible form of structure description:

START

Mo1 net starts with Mo1 process object

Mo2 or Mo4 or Mo3 net splits, Mo2, Mo4 or Mo3 can be selected
IF Mo2 THEN Mo7
IF Mo3 THEN Mo5 subs Mo6 on the Mo3 branch Mo6 follows Mo5
IF Mo7 OR Mo4 or Mo6 THEN Mo8 Mo7, Mo4 and Mo6 is joined to Mo8
Mo9 the last process object is Mo9
END

The feature is adapted according to the description of manufacturing task. Figure 5(b)) shows a net in which Mo7, Mo4, Mo6 and Mo8 are unnecessary (on the basis of analysis of the manufacturing task and the manufacturing environment description) and so they have been deleted. For example, reaming and counterboring are not necessary for the given manufacturing and presently there is not available tool for the Mo5.

Figure 5 Creating process feature structure

Using the modified basic net structure the Petri net model of the process feature is generated (Figure 5(c)). First transitions are generated for each process object. Then splits and joins are generated. Following this, place objects are generated and put before the transitions and initial marking is created. If rules are available for a transition, their identifiers are placed in the appropriate attribute of the process object represented by a transition. Rules for selection of a given transition are attached to the place that precedes it. These are simple IF ... THEN ... ELSE rules. They contain attribute values for manufacturing tasks, process objects and manufacturing environment objects. In this manner structured and unstructured information for the given manufacturing process feature is organized into a Petri net structure. At this point the Petri net representation of a generic process feature is ready for evaluation.

Knowledge and dedicated procedures serve calculation of attribute values of the manufacturing process objects represented by transitions. Changes in initial conditions of the process planning may require changes not only in sequence of process elements in the process plan but changes in values of their attributes too. Elements of a Petri net model can be interrelated using special purpose rules. Process model features and Petri net elements are

defined as objects. Petri net objects are net, place, transition, arc and token. Instances of these objects are generated as manufacturing process model entities.

Figure 6 The process model for a part

The process model for a manufacturing task is outlined in Figure 6. Petri net representations are related through transitions. There is a Petri net for the process (PN_{pr}) and another for the net of setups (PN_{set}). Two or more nets of setups can be defined for a process as it can be seen in the example later in this paper. Two sets of Petri nets of operations are stored for setups (PN_{ops1} - PN_{opsn}) and for manufacturing of form features (PN_{opf1} - PN_{opfm}). Transition has pointer to the process object data. Manufacturing process generation procedures search rules in a structured central rule base where IF-THEN rules can be placed by manufacturing and systems engineers. Rules have been introduced by the authors in (Horváth, L. and Rudas, I. J., 1995).

5. PETRI NET FEATURE REPRESENTATION EXAMPLES

A typical example of manufacturing process model for a prismatic part machined in a flexible manufacturing system was generated. In the course of the run experiments the effect of typical initial conditions on the manufacturing process was simulated.

Figure 7 Form features on the test part

Figure 7 shows the form features that were defined on the prismatic test part. Typically form features are arranged on the six sides of a prismatic part. At this example only three sides contain features to be machined. Manufacturing process can be realized by two different nets of setups (Figure 8). These alternatives are represented by the t_{nset1} and t_{nset2} transitions in the Petri net.

Figure 8 Process feature

The net of setup $nset1$ is represented by a Petri net that contains transitions for setups applied at manufacturing of the sides of the part (Figure 9). The part manufacturing starts with a setup for machining datum surface and ends with an end inspection. Two alternatives are machining sides in two (set2 and set3) or three (set4, set5 and set6) setups.

Figure 9 Net of setup and net of operations features

Attributes of the setup object describe the type of setup, the machine tool, the datum surfaces, etc. Figure 9 shows the net of operation feature for the $set4$ setup. This setup

involves operations that are needed for machining of form features on the upper side of the part. After machining the face F1 completed, the channel C1, the boss B1 and the pocket P1 are machined in separated or common operations. The latter is the case of using common tool for manufacturing of these form features. The structure of the Petri net was created to represent the above process variants.

Figure 10 Net of operations feature

The focus in this paper is limited to the generation of the process model. Data base that contains information about the required knowledge is assumed. Evaluation procedures are not discussed. In practice, procedures for manufacturing process planning are attached to software packages included in CAD/CAM systems, production planning and scheduling systems and flexible manufacturing systems. The integration of manufacturing process model generation methods into these environments requires additional investigation. An another problem is related to interactions between the generation procedures and the human planner (Horváth, L. and Rudas, I. J., 1994/2). The cooperation of well-known problem solving, process planning and Petri net evaluation procedures with the process modeling environment and the related interfaces are topics of future research.

6. CONCLUSIONS

A method for modeling of manufacturing processes has been proposed by the authors. Demands of CAD/CAM and flexible manufacturing systems have been taken into consideration. Feature based modeling approach and Petri net representation for model entities were applied. The main contributions of this paper are:

- A product model approach to manufacturing process modeling was shown.
- Petri net representations of generic manufacturing process features were introduced. These features were placed into a four leveled model structure.
- Generation of process model entity using classification trees, structural description and unstructured knowledge was explained.

The proposed method has proved to be suitable for modeling real world processes. Models can be evaluated by executing the Petri nets taking into account requirements of both process planning and production scheduling. The results of experiments are promising. Integration or interconnection manufacturing process models with manufacturing system models (Kovács, G. and Mezgár, I. and Kopácsi S., 1994) is an exciting task for future research.

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9 BIOGRAPHY

László Horváth received the MSc degree in Production Engineering from the Technical University of Budapest in 1971, received the Dr. Techn. degree in computer aided process planning systems from the Technical University of Budapest in 1984 and received the Ph.D. degree in knowledge based process planning systems from the Hungarian Academy of Sciences in 1992. He is active as professor at the Bánki Donát Polytechnic, Budapest, Hungary where currently teaches courses on CAD/CAM systems engineering and knowledge engineering. He is member of the New York Academy of Sciences, Senior Member of IEEE Industrial Electronics Society, IEEE Systems, Man and Cybernetics Society and IEEE Human-Computer Interaction Technical Committee. His research interests include modeling of manufacturing processes, application of artificial intelligence in manufacturing process planning, integrating design and planning systems, concurrent and collaborative engineering, product modeling and human-computer interaction.

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