International Journal of Industrial Engineering and Management (IJIEM), Vol.1 No. 1, 2010, pp. 9-18
Available online at http://www.ftn.uns.ac.rs/ijiem
ISSN 2217-2661

Distributed Modeling of Manufacturing Activities using Integrative Manufacturing Process Model

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Received (17.05.2010); Revised (24.05.2010); Accepted (04.06.2010)

Abstract

Process planning is one of the key activities for product design and manufacturing. Impact of process plans on all phases of product design and manufacture requires high level of interaction of different activities and tight integration of them into coherent system. In this paper we describe a model for manufacturing activities that allows such integration. The framework for integration is briefly described and the integrative manufacturing process model (IMPM) that considers three dimensions of planning is explained. Manufacturing process model is described as three-dimensional model with the following dimensions: time/order, variability/alternatives, and aggregation. All dimensions are defined and explained as they are related to overall manufacturing planning. The nature of these dimensions is illustrated with several examples. The formal description of the IMPM model is provided usign the graph theory as the basis for the model implementations. Several implementations of the model in Lisp and Java programming languages are are enumerated and applications that generate the model are described with few examples.

Key words: *CAPP, manufacturing planning, process plan modeling*

1. INTRODUCTION

Developments in Computer Integrated Manufacturing have focused for a long period of time in linking various automated activities within the enterprise. However, the complexity of manufacturing process itself and extended application of computer supported equipment has led toward identifying three main phases in manufacturing integration [6]: (1) hardware and software integration, (2) application integration, and (3) process and people integration. After several years in focusing on CAD/CAM integration, the research has moved toward the third phase, process integration. One of most important links for implementation of integrated manufacturing is process planning, the link between product design (CAD) and production planning and execution (CAM, MES). This paper addresses an issue of generating and viewing process information within the integration framework. The paper is organized as follows. The section 2 brifly describes previous work in manufacturing integration. The section 3 describes interactions between manufacturing planning functions and identifies the need for integration. Section 4 section explains integrative manufacturing process model and its formal description. Section 5 enumerates several model implementations and section 6 explains applications that generate the model projections. The paper ends with concluding remarks and the list of consulted references.

2. PREVIOUS WORK

There are numerous papers devoted to various process planning systems which achieve certain level of manufacturing planning integration. Early major CAD/CAPP integration works are Nextcut at Stanford [1] and QTC at Purdue [4]. These systems provide the integration between CAD and CAPP systems and, in some cases, provide the actual machining on NC machine connected to the system (as in QTC). However, these concern a one-way integration from CAD to CAPP, and further to NC code generation and actual machining. Recent research efforts are devoted to generation and evaluation of alternative process plans and to enlargement of manufacturing knowledge base. The system described in [11] performs process planning and manufacturability analysis for machining operations in order to satisfy position tolerances. The system considers several alternatives and selects as optimal the plan with minimum number of setups. IMACS, the system that evaluates alternative process plans by analyzing alternative feature volumes to be removed is reported in [7] and [8]. PART [12], a process planning system developed at University of Twente and built into commercial product Technomatix(c) combines feature recognition and process planning into an integrated system and performs process and tool selection, selects cutting parameters, and generates tool paths which can be post-processed for generation of NC code. The system uses a relational database for permanent storage of features and process plan. Application of CAPP methodology has been also extended to few specialized domains, such as sheet metal manufacturing. Integration framework for data and knowledge modeling of design and process planning for sheet metal components has been reported in [28]. A domain independent shell for DfM has been proposed in [29] and its application in metal forming and injection molding demonstrated.

Integration with other manufacturing planning functions is reported in several papers. Research reports [5] [16] aim at integration of process planning and scheduling functions. Another research project was reported in [14] with the goal of integrating of process planning and shop-floor control. The authors provide the process plan representation to be used in shop-floor control that carries hierarchical representation of process plans and alternative process plans. Several research papers address issue of alternative routing in cell formation procedure [24] [25] but do not address the issue how to generate alternate routings. Several methodologies that address process planning and scheduling integration are described in [30].

The issues of data and knowledge representation and integration framework have also received significant interest. From an early work on ALPS [3], there have been several reports devoted to these issues. Some papers address knowledge representation, using hierarchical abstraction [15] or object-oriented data model [18]. Recent results are in generation of the Process Specification Language (PSL) as a neutral format for interchange of process representation. Major issues being addressed in this project are transfer of both syntactic and semantic information between application that deal with various facets of process design and decision making procedures. Details about the PSL project may be found on NIST web site (www.nist.gov). Paper [33] integrates concepts of PSL with STEP standard and proposes flexible approach for global NC manufacturing. The structure of the manufacturing knowledge model and its functionalioty in software are presented in [34].

Recent work in CAPP was significantly influenced by expansion of internet technologies and distributed computing. Concept of autonomous and intelligent agents as actors for manufacturig planning has been proposed in [31], while paper [32] demonstrates an agent-based approach for distributed and decentralized process planning and NC control. This direction has been extended in [35] by introduction of holons to provide synchronisation and interoperability between physical world and information world within a distributed enterprise.

3. MANUFACTURING ACTIVITY INTERACTIONS

The product development and manufacture involves several production management activities with a series of individual tasks that are to be completed in order to design and manufacture a product of a required quality. These tasks are usually carried out in a linear sequence, but very often the feedback is necessary from the subsequent task to the previous one. Many of these feedback loops are requests to modify the previous task's solution in order to generate a better solution in the subsequent one. This interlinking is what has become known as concurrent or simultaneous engineering.

In this section we will provide a model of these activities and tasks and identify how these tasks connect high-level activities. We identify need for integration from the whole product development cycle perspective, and, after that we describe an extensive set of manufacturing planning tasks which are components of manufacturing activity model.

3.1 Need for integration

Product development cycle may be seen as a set of answers to a series of simple questions [9]: WHY? WHAT? HOW? WHERE? WHO? WHEN? to produce. When we find answers to these questions we will actually identify what functions are necessary in the cycle from developing an idea to the realization of the final product. Answers to these simple questions may be given by connecting them with particular manufacturing functions (Fig. 1). Answer to the question WHY organize manufacturing at all is given by marketing function. WHAT to produce in a company is the result of design function. Detailed instructions on HOW to make product are generated in a function called process or production planning. This function actually represents technological knowledge and defines competitiveness of the manufacturing company.

The answers to questions WHERE and WHO are obtained from resource (or facility) planning function, which is responsible for facility, machines, equipment and workforce. Finally, the decision regarding WHEN to manufacture is made by a production control function. From sparking an idea to realize mental creativity of an individual, all way to the realizing a final product it is necessary to go through all of these functions. However, we are not saying that getting answers to these questions is easy.

Behind each of those functions there is smaller or larger set of engineering tasks which have to be completely performed in order to make the function successful in the product development cycle. Nevertheless, it is worth pointing out that this basic model allows us to capture the very nature of manufacturing. This figure also shows that product development cycle is not a linear path without obstacles. Usually, the product development follows some zigzag pattern between functions with frequent needs to feedback information form a function to its predecessor.

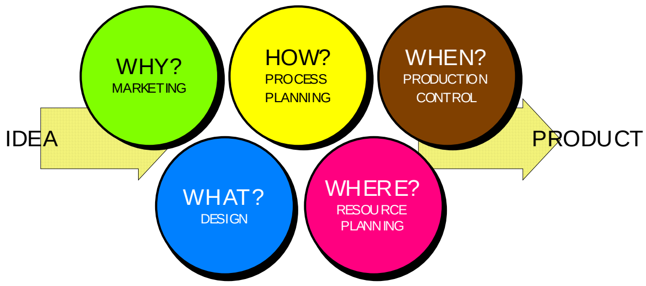


Figure 1. Basic product development planning functions

Further analysis of these functions reveals that while they are being performed there are numerous feedback loops and some of tasks within the functions can not be easily assigned to one or another. In that case we have an overlapping of these functions. For example, in metalworking industry it is possible to identify the following functions: design, feature recognition, process planning, resource planning, and scheduling (Fig.2). These functions are not independent and they can not be performed independently. For example, machine selection for a particular part in process planning depends on machine load from other parts, which is usually determined by scheduling function. Therefore, we can identify some production planning tasks that can not easily be classified into particular function. These tasks belong to intersections between functions and necessarily lead toward integration between these functions.

3.2 **Manufacturing Activity Model**

Starting from the above discussion and analyzing set of tasks of process planning and other activities it is possible to develop the model that shows interactions between process planning and them. The model of these interactions is shown in Fig. 2. As it may be seen from the figure, each activity consists of a set of tasks that are to be done in the product development. All of these activities are identified in manufacturing planning literature as activities necessary or required during the product development and manufacture. The classification shown in Fig. 2 is the result of author's research work and represents a starting point for the use of this method in each individual factory. For example, creation of the solid model of the part is done in design, while manufacturing resource planning is done within resource management. However, there are numerous tasks that require interactions between two or more activities. They are shown within overlapping circles of activities and represent integration links. For example, setup planning is part of process planning, but also needs information about scheduling for efficient setups, or feature modeling belongs between design, feature recognition, and process planning.

Let us consider another example, in the interaction of design and process planning functions. One of tasks in the product development is stock selection (material and shape), as a part of product design. However, by defining the part material we may reduce alternative manufacturing processes, for example by selecting cast iron as material, we decide that casting process is required and later machining processes involve only needed finishing of small number of part faces. In another case, if we define a sheet metal as stock shape, some pressing or deforming operations are necessary.

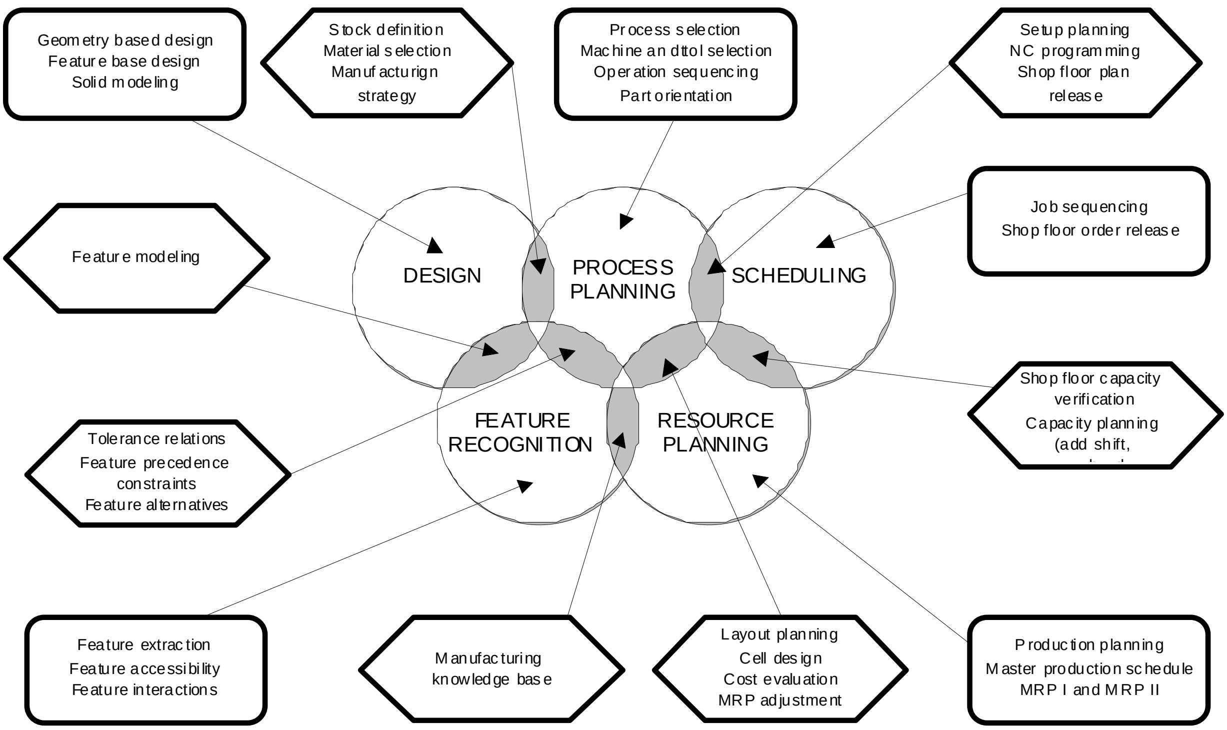


Figure 2. Product development tasks

Another example is related to resources and manufacturing features. The set of manufacturing features that can be machined by various manufacturing processes is completely defined and constrained by the kind of machines and equipment within factory. For example, if we have lathes and mills in our shop floor, it is obvious that our technology is constrained on machining processes. If a company owns plastics presses, the technological knowledge of the company is in plastics manufacturing. Therefore, the part of resource planning function is also development of manufacturing technology (in machining that is extension of manufacturing feature taxonomy within a factory).

It is important to understand above explained interactions in order to completely utilize engineering knowledge and expertise. Each of these activities needs specialists in its domain, while intersections need group work and they are suitable for applying concurrent engineering principles. The most important intersections from process planning perspective are: between design and process planning related to part family formation, between process planning and resource management related to manufacturing cell design, and between process planning and scheduling related to production control of cells.

After we understand the above interactions, the next question is how to utilize them in order to achieve integration. There are numerous methods that serve the purpose of manufacturing integration (e.g., DFM, DFA, group technology, cellular manufacturing, production flow analysis, simulation, etc.) We propose that one important ingredient is needed: generation and consideration of alternatives between individual manufacturing planning functions. In the next section we propose an integrative manufacturing process model that incorporates generation of alternative process plans and allows dynamic integration of process planning and other planning functions.

4. INTEGRATIVE MANUFACTURING PROCESS MODEL

In this section we describe the integrative manufacturing process model (IMPM), which is a graphical model for representing planning functions and tasks for manufacturing processes. First, we explain the model dimensions: variety, time and aggregation. After that we provide a formal definiton of the IMPM which is the basis for its implementation.

4.1 Model Dimensions

The basic entity of the manufacturing process model is a process, intuitively understood as an activity, usually planned in advance, with all necessary attributes. All manufacturing planning functions generate various planned tasks or activities (e.g., cutting with turning cutter, deforming with a press, machining on a single machine, processing job order, etc.). Each of these tasks (manufacturing execution tasks) has numerous attributes, that have to be defined before the task can be undertaken (e.g., for cutting with turning cutter, one has to define part, tool, cutting parameters, space orientation of part and tool on a lathe, starting time, ending time…). As we have explained earlier, these attributes are usually defined by different manufacturing planning functions. In this section we identify the dimensions of a model that are independent of planning function, require transfer or translation from one function to another and facilitate manufacturing integration.

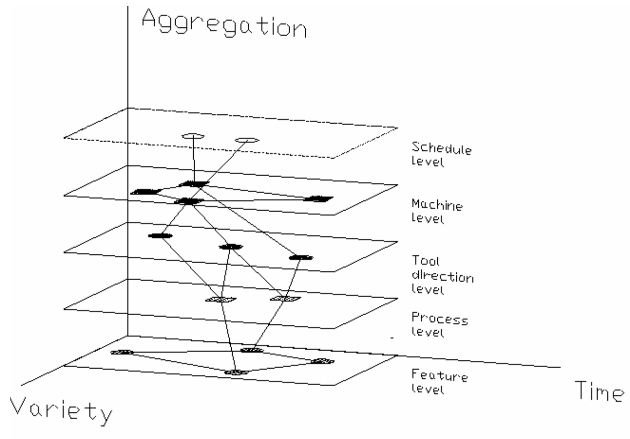


Figure 3. Manufacturing process model dimensions

The manufacturing process model consists of three dimensions (Fig. 3): time, variety and aggregation. Each manufacturing process is related to other processes with respect to these three dimensions. The time dimension describes relative temporal relation between several processes of the same type. This relation has several levels of certainty. The lowest level is when we specify that some (planned) process has to be performed before or after another process (this relation is known as precedence constraint). Example of this relation is the existence of the constraint that one manufacturing feature has to be machined before or after another (e.g., the hole has to be drilled after the surface has been milled, if that surface was cast earlier). The time relation may be refined until final determination that these two processes have specified starting and ending times such that they have to be performed in non-overlapping time intervals. An example of this relation is the case of the manufacture of two parts on the same machine, or consideration of two operations (on different machines) on the same part. The very important property of this relation is its transitivity. The transitivity holds between processes on the same level (this corresponds to the definition of an order relation in mathematics), as well as between the processes on different levels (in this case the relation is inherited or transferred from one level to another). However, due to the variety dimension of the model this relation does not impose total order. The relation orders various manufacturing processes only partially, that is to say, between some processes relation is true, while some processes are not ordered. In the latter case, therefore, the processes may be performed in any order, or in some cases in parallel.

The variety dimension describes sets of different processes that are generated within a certain level. Usually it is necessary to define a set of different processes in order to complete the manufacturing task. For example, when we define the process plan for a given part, there is a set of features that require a set of cutting processes. Also, one feature may require more than one process, for example, a hole may require drilling and reaming. Another way for generation of different processes is generation of alternatives. For example, in selection of cutting processes, there are usually several alternative cutting methods to machine the same feature, a slot may be machined by end milling or side milling, and so on. The variety dimension in the manufacturing process model is present also when we consider manufacturing of different parts or products, and when we use different machines to manufacture the whole product range.

The aggregation dimension relates to various scopes of planned processes. Processes are defined with different levels of details, time frame (duration). Also, usually a set of manufacturing processes, planned in one function, may be considered as a whole in another planning function. For example, in process selection the cutting process for each feature is considered separately, in setup planning these processes are combined for the same machine, while in scheduling the whole process plan for the part is considered as a unit. Therefore, this dimension explains that some process is a part of another process with the same part, machine, tool or some other attribute. This is necessary in order to distribute planning tasks among different functions. In the above examples, different levels of aggregation allow different planning tasks (process selection, setup planning, and scheduling in the example) to focus only on attributes relevant for the task. For example, in the process selection task of process planning function, someone is concerned only with the quality of the part, while during scheduling the main concern are delivery dates for the products. Therefore, aggregation is performed when we combine processes of lower level that have some attribute in common in order to perform planning on that level.

Three explained dimensions are not independent. The relations that hold between processes in one dimension impact other dimensions as well. For example, the precedence order on the feature level has to be replicated on all other levels when process planning is performed on the machine level. Scheduling and machine load constraints may have an impact on process plans in terms of selecting an alternative plan which may balance the machine load. Generation of alternative cutting processes and selection of alternative machines or tools for individual features requires generation of alternative operations on the machine level and provides choice of the most suitable alternative at scheduling level.

Overall manufacturing planning activity creates such a model in a distributed fashion (i.e., several specialists with different knowledge are involved), and the model is subject to change as manufacturing planning and/or execution progresses.

4.2 Formal Model Description

The informal descripiton of the model given in the previous section corresponds to a definition of a graph with multiple relations, whcih we will name a multigraph[*]. The multigraph Gm = <N, R, A> is defined by a set of nodes N, set of relations R, and set of arcs A such that aE A implies that there exists an r E R, such that for two nodes n1 and n2 it ios true that n1 ri n2. That is to say, a multigraph is defined by a set of nodes (objects), a set of relations between those objects and a set of arcs which correspond to facts that nodes are connected by specified relations. In the case of Integrative manufacturing process model, set of nodes corresponds to process plannig objects, namely, features, feature operations, setup operations, machine operations, and process plans. Relations correspond to compatibility relations between features and processes, aggregation relations that establish a membership of a process in an aggregate process, alternative relations which establish AND/OR relations between objects, and precedence relations which establish a temporal relationships between objects. Important property of the multigraph is transitivity of relations, which should be defined differently fro a regular graph. In a multigraph transitivity is defined over two relations, whcih are defined in different dimensions. For relation ri to be transitive the following condition should be met: if N1 ri N2, and N1 rj N1' and N2 rj N2' than we define that N1' ri N2'. An example of this transitivity can be explained on a precedence relation: if a process p1 should precede p2, and p1 is a member of p1', and p2 is a member of p2', than precedence relation should hold between p1' and p2'.

Having established a general definition for the IMPM it is possible to apply several projections from the IMPM. For that purpose the following definition can be used:
A graph G = <Ng, Ag> is a projection of Gm if Ng is subset of N, Ag is subset of A such that for every ai in Ag, it is true that ai defines Ni Rg Nj for a unique Rg E R. The various choices for Ng and Rg can lead to various projections from IMPM:
- Aggregation tree, which is defined for a single root node Ng and membership relations from this node to other nodes
- Precedence network, which is defined for a single level, collects all nodes at that level that are members of a single root node, and include precedence relations between those nodes
- Association matrix, which is defined for a single level without root node and includes all nodes that have shared property value, for example all operations on various parts that belong to the same machine. Several of these projections will be explained later on examples in section 6.

[*] This definition of the multigraph is not the same as definition in graph theory literature.

5. IMPLEMENTATIONS OF INTEGRATIVE PROCESS MODEL

The integrative process model has been implemented by the author in several variations:

- Integrated implementation with automatic IMPM model generation has been implemented in the Intelligent Integrative Incremental Process Planning (3I-PP) system [13]. The system has been implemented in Lisp with two ports: Lisp/KnowledgeCraft port and Lisp/CLOS port. Both systems apply the same algortihm for process selection and sequencing from a feature based part model and automatically generate the IMPM for a given part. They also use the same knowledge base, but they provide different user interfaces.
- User guided IMPM implementation with semi-automatic generation of the IPM in phases has been implemented in Intelligent Manufacturing Planning (IMPlanner) System [22]. The system has been implemented in Java with direct integration with CAD system and it provides high fidelity level of user interations in the model development. Process selection has been implemented as a rule-based system using Jess [19], while process aggregation is user guided. In addition the modules for process visualization of slots and pocket machining has been implemented. The use of Java technology enabled direct remote access using applets and model deployment as web service.
- Distributed implementation of the IPM has been added to the IMPlanner to allow distributed collaborattion. For this implementation, portions of the IPM are stored into XML formats and transferred between various aplications. The particualr feature of the XML transfer mechanism is that it allows for different XML formats, dependent on the application at hand [27].
- Agent-based implementation is under way to enable further flexibility. The agent technology will enable intelligent and automonous discovery of services and their utiliation in order to globbaly optimize manufacturing process. The link with manufactruing execution systems is also planned.

6. APPLICATIONS

In this section we provide an overview of applications that use different submodels of the IMPM which are in fact projections of the IMPM (as defined in section 4.2) into various specific manufacturing planning activities and tasks.

6.1 Aggregation trees

Aggregation trees are projections of the IPM onto aggregation/variety plane with a single node at the highest level. Projection views have been implemented in IMPlanner for two types of aggregation trees: Feature/process tree and Process plan tree. An example of the feature process tree for a sample part in Fig. 4 is shown in Fig. 5.

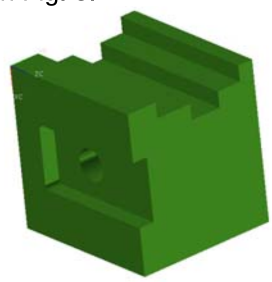


Figure 4. Netex example with six features

The rooot of the tree is a part model, which contains a set of features. As visible form the figures the part has 6 features and feature/process tree in Fig. 5 shows all manufacturing process requirements and alternatives for each feature.

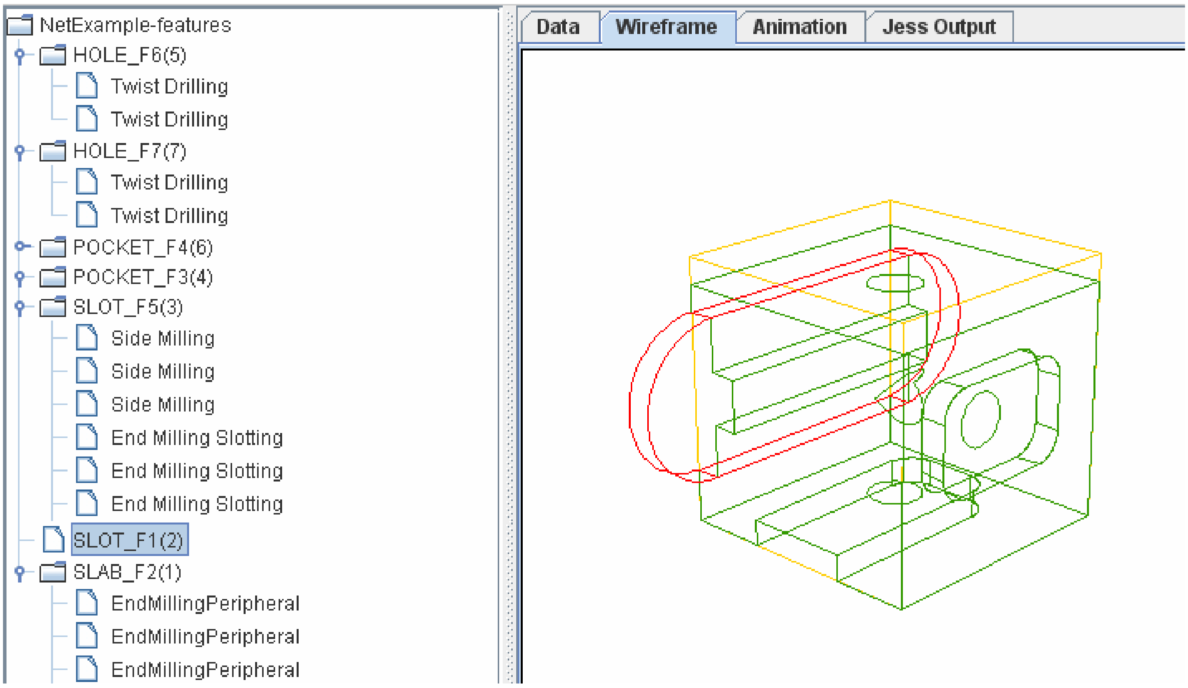


Figure 5. Feature process aggregation tree for Netex example

Alternative processes are shown as parallel nodes under each feature node and multiple required processes are shown as a process hierarchy under the feature. IN thsi example fro slto featur etwo alternative processes are considewred: end milling and side milling. In addition alternative processes are result of using alternative tools and machine savailable on the factory floor. The representation also provides for details of each node, with showing the feature geometry on example in Fig. 5.

The process plan tree shows the part processig breakdown after the process plan selection is complete. An example is shown in Fig. 6 and 7. The Fig. 6 shows the same feature/process tree in a different example, housing, that was done for industrial partner[20], [23]. This tree shows alternative methods to make hole features in cast part: boring, reaming, or precision boring. In this example the user has an option to configure machine operations interactively by selecting features that should be done together. The Fig. 7 shows the resulting tree. The root of the tree is a part that needs to be produced. Subnodes correspond to a decomposition of the process plan onto different machines, then onto different setups, tools and finally the leaves of the tree are machning processes for each feature, which are chosen from the previous tree.

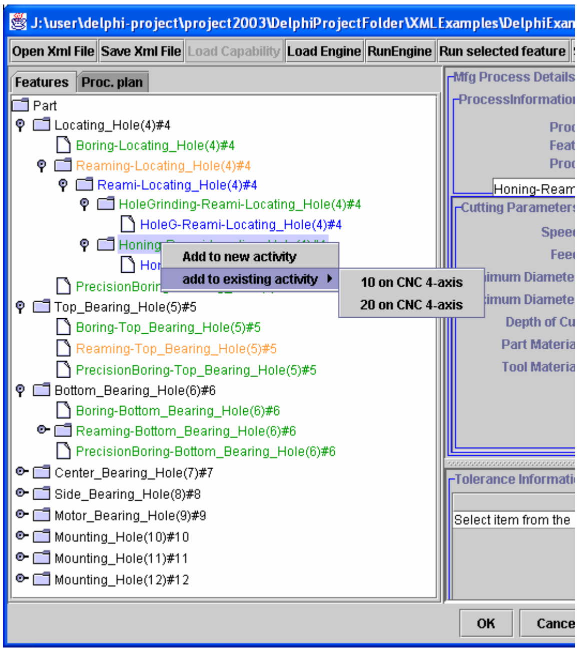


Figure 6. Feature/process tree for Housing example

6.2 **Precedence networks**

Precedence networks are projections of the IMPM onto time/variety plane with the nodes at the same aggregation levels. These views have been implemented for two networks: FPN (feature precedence network) and PPN (process precedence network).

The FPN is a result of the design for manufacturing analysis performed on a part feature model to detect manufacturing constraints imposed by feature dimensions and tolerances. An example of the FPN for the part shown in Fig. 4 is shown in Fig. 8. As shown the FPN is a directed graph from start node to end node in which arrows show imposed precedence. For example F6 has to be machined before F2 and F3 in our example.

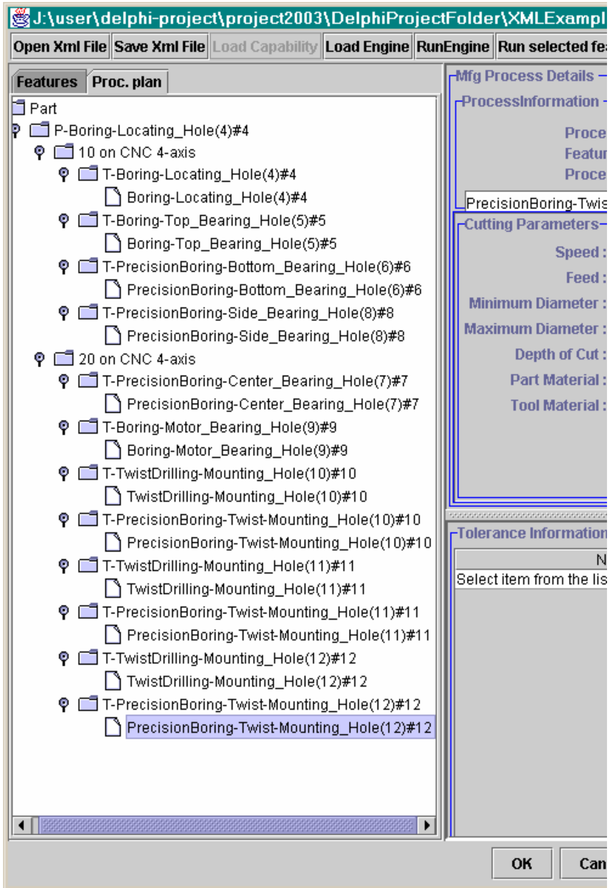


Figure 7. Process plan tree for Housing example

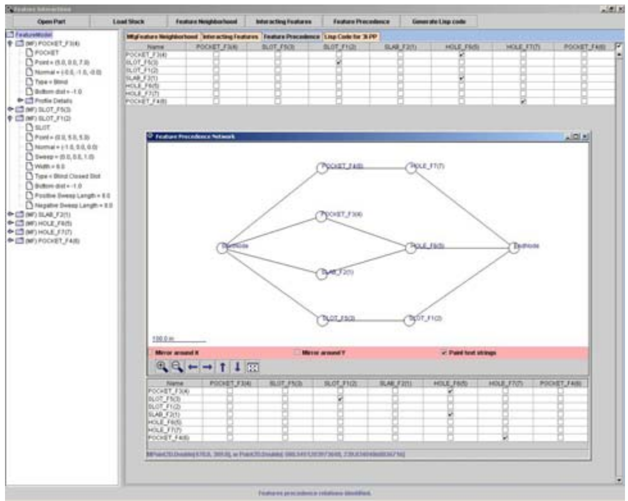


Figure 8. Feature Precedence Network for Netex example

Process plan network is a result of process sequencing and clustering in order to develop alternative process plans for the part. The resulting directed graph (Fig. 9) [20] shows all alternative ways to make a part, in such that any path from START node to END node correspond to a process plan alternative. Important property here is that each node in this projection may serve as a root node for aggregation tree which would produce a tree similar to the one shown in Fig. 7. The best alternative is usually chosen by applying dynamic process planning.

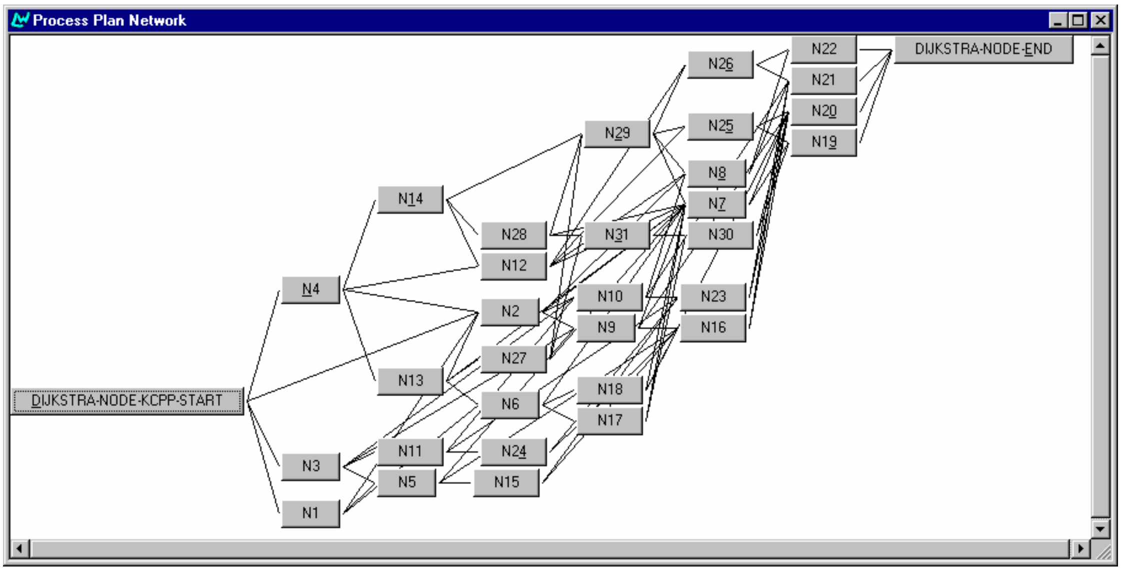
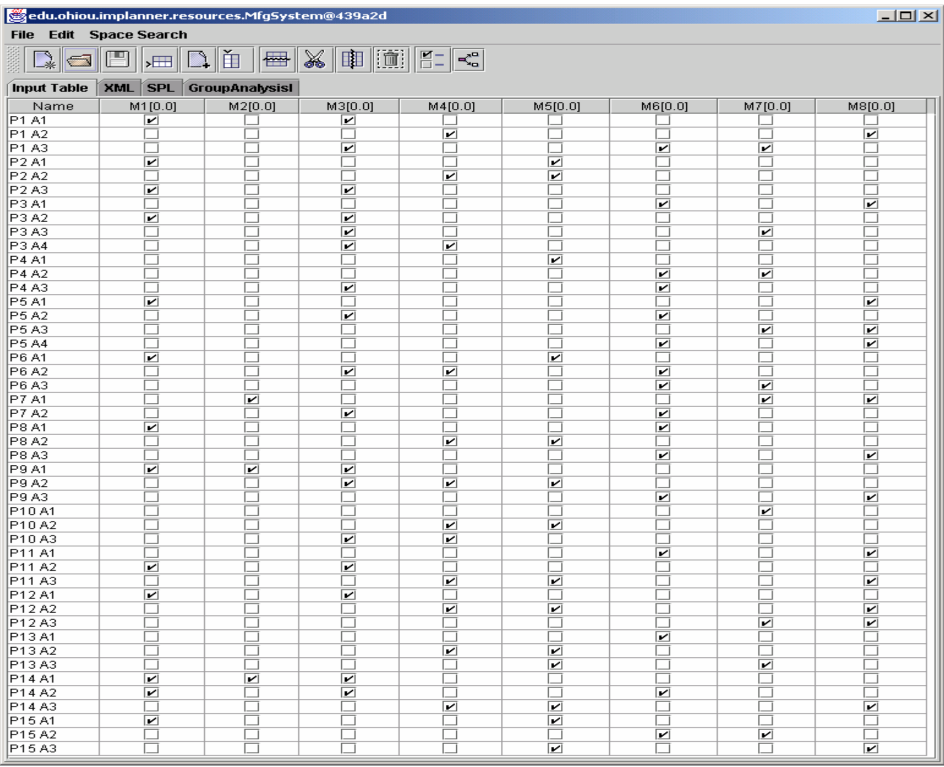


Figure 9. Process plan network for Netex example

6.3 Part machine matrices

Part machine matrices are projections of the IMPM onto time/variety plane at the highest level of manufacturing planning. They serve the purpose of providing high level plan information for other production planning tasks, such as cell formation, scheduling, simulation, or shop floor control. They may be used as final process plan information, or they may include alternatives in order to apply integrative algorithms. An example of part machine matrix extracted from the IMPM for a manufacturitng of 15 parts on eight machines is shown in Fig. 10. This matrix may serve as an inoput to cell formation procedure or a schedluing algorithm. Example shown provides for inlcusion of alternative process plans into those algorithms. Thise example was used as an input for a cell formation procedure with alternative plans described in [26].



Name	M1[0.0]	M2[0.0]	M3[0.0]	M4[0.0]	M5[0.0]	M6[0.0]	M7[0.0]	M8[0.0]
P1 A1	✓		✓					
P1 A2				✓				✓
P1 A3			✓			✓	✓	
P2 A1	✓				✓			
P2 A2				✓	✓			
P2 A3	✓		✓					
P3 A1						✓		✓
P3 A2	✓		✓					
P3 A3			✓				✓	
P3 A4			✓	✓				
P4 A1					✓			
P4 A2						✓	✓	
P4 A3			✓			✓		
P5 A1	✓							✓
P5 A2			✓			✓		
P5 A3							✓	✓
P5 A4						✓		✓
P6 A1	✓				✓			
P6 A2			✓	✓		✓		
P6 A3						✓	✓	
P7 A1		✓					✓	✓
P7 A2			✓			✓		
P8 A1	✓					✓		
P8 A2				✓	✓			
P8 A3						✓		✓
P9 A1	✓	✓	✓					
P9 A2			✓	✓	✓			
P9 A3						✓		✓
P10 A1							✓	
P10 A2				✓	✓			
P10 A3			✓	✓				
P11 A1						✓		✓
P11 A2	✓		✓					
P11 A3				✓	✓			✓
P12 A1	✓		✓					
P12 A2				✓	✓			✓
P12 A3							✓	✓
P13 A1						✓		
P13 A2				✓	✓			
P13 A3					✓		✓	
P14 A1	✓	✓	✓					
P14 A2	✓		✓			✓		
P14 A3				✓	✓			✓
P15 A1	✓				✓			
P15 A2						✓	✓	
P15 A3					✓			✓

Figure 10. Part-machine matrix for 15 parts

7. CONCLUSIONS

In this paper we have described integrative manufacturing process model as a basis for distributed application of CAPP and intelligent information integration. The model is based on analysis of interactions between various planning functions. The very important role of process planning function, as the function which defines manufacturing processes has been emphasized.

Manufacturing process model consists of three dimensions: time, variety, and aggregation. The transfer of relations from one dimension to two others further connects these dimensions. Several model implementations are described and applications that generate the model projections are explained. In such way, this model enables dynamic process planning by introducing changes in design, machine status, etc… and propagating them through the model graph.

The current implementations of the IMPM, and corresponding applications are currently being explored as a model for development of distributed virtual manufacturing with autonomous intelligent agenss as carriers of tasks and infornmation through the network by discovering the services.

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