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PIM:
Planning In Manufacturing using Skeletal Plans and Features

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PIM:
Skeletal Plan based CAPP

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Abstract

Abstract. In order to create a production plan from product model data, a human expert thinks in a special terminology with respect to the given work piece and its production plan: He recognizes certain features and associates fragments of a production plan. By combining these skeletal plans he generates the complete production plan.

We present a set of representation formalisms suitable for the modelling of this approach. When an expert's knowledge has been represented using these formalisms, the generation of a production plan can be achieved by a sequence of abstraction, selection and refinement. This is demonstrated in the CAPP-system PIM, which is currently developed as a prototype.

The close modelling of the knowledge of the concrete expert (or the accumulated know-how of a concrete factory) facilitate the development of planning systems which are especially tailored to the concrete manufacturing environment and optimally use the expert's knowledge and should also lead to improved acceptance of the system.

1 Advantages of knowledge-based systems - Problems in CAPP

Systems to support CAPP encounter a particular problem which arises out of the structure of this domain: In order to create a successful process plan it is not sufficient to rely on theoretically founded rules - which normally can be coded into a program quite easily - but it is also necessary to consider particularities of the production environment and special experience of human process planers. The latter is very often difficult to formalize and consequently hard to be coded, the former may change radically between different working environments and leads to a high maintenance workload.

Under this circumstances the knowledge-based programming methodology may be used: If it is possible to define domain-oriented languages facilitating the explicit representation of the knowledge in question and to provide adequate execution mechanisms for these languages the problem becomes treatable. Suitable representation languages lead to easier representation of the experience and environment-dependent knowledge. The execution mechanisms are independent of the environment and probably useful in a broader domain, thereby reducing the general maintenance workload.

In summary, knowledge-based programming may lead to higher flexibility of the system, easier adaptation to changing environments, reduced maintenance costs, and successful solutions of some problems which can't be tackled with standard techniques.

Several projects currently try to use knowledge-based methodologies in this context (cf. the ESPRIT.projects IMPACT, PLATO, FLEXPLAN [Espr89]). In the project ARC-TEC at the DFKI Kaiserslautern, these general ideas where exemplarily applied to the automatic generation of work plans for manufacturing by cutting with geometric defined cutting edge (DIN 8589 part 0), resulting in the prototypical system PIM (Planning In Manufacturing). The developed methodology is of interest for CAPP in general.

2 CAPP from the viewpoint of knowledge-based systems

In order to create a knowledge-based CAPP system, we examine the way a human expert solves the task in question. This leads to the following general model of a process-planning method:

The expert is given the description of the work piece. This description consists of all geometrical and technological data which are necessary for the generation of the process plan. In this description the expert identifies characteristic parts or areas which contain special information about the manufacturing process. According to these so-called application features, the expert selects out of his memory (or out of existing plan libraries) generalized plan fragments, the so-called skeletal plans. By combining these partial plans and by adapting them to the concrete work piece, he creates the complete production plan. [Teng84]

The combination of application features and associated skeletal plans represent the experience of the expert. (An expert may be defined as someone who knows "what to look for" and, having found this, what to do about it). It is important to realize that this observation implies that the application features and the skeletal plans depend on the concrete expert as well as on the concrete working environment and may be different for another expert or another environment.

From the viewpoint of knowledge-based programming the above description leads to the identification of several representation tasks. It is necessary to represent the work piece information,and the application features and the associated skeletal plans of an expert in a given working environment. Together with a execution mechanism which mimics the sketched method of the human expert, a flexible and reliable CAPP system is possible. [Bern91a] The following chapters describe the different representation languages which were developed in the ARC-TEC project according to figure 1.

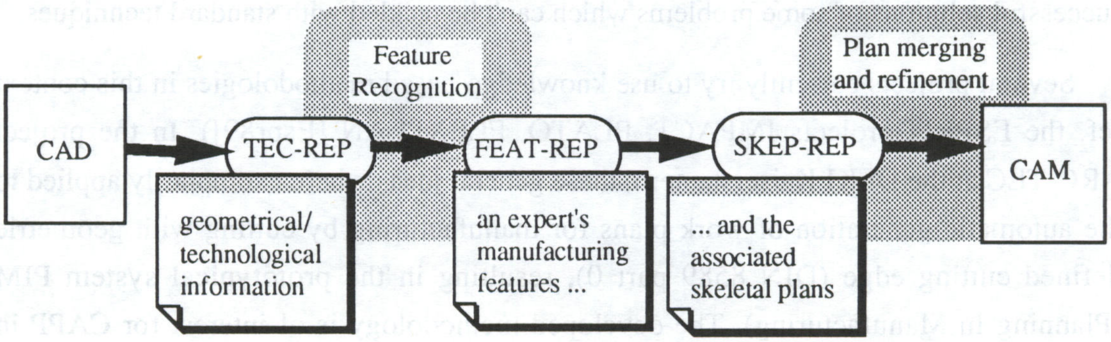


Figure 1: Basic idea and representation languages

3 TEC-REP

The representation formalism TEC-REP [Bern91b] provides the necessary constructs to describe the geometrical and technological information of the work piece. The description must contain all information about the work piece which an expert may use to create the process plan. In order to facilitate the necessary deductions the representation formalism should use symbolic expressions. As shown in a later chapter the TEC-REP formalism is well connected to the CAD-world.

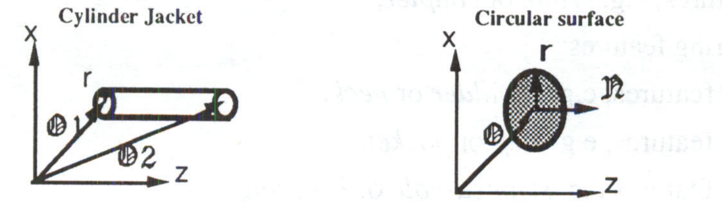
In TEC-REP, the geometry of a work piece is described by surface primitives. These predefined primitives include simple expressions for rotational symmetric parts, which are of special interest in the domain of manufacturing by turning. To be as universal as possible, primitives for non-symmetric surfaces also exist. The extensions of any surface are specified using a cartesian coordinate system. The concrete dimensions are specified for each work piece. Every surface of a work piece description can be identified by a unique identification number.

TEC-REP realizes a simplified boundary representation of the geometry of a work piece. While some surfaces like free formed surfaces which aren't considered in the ARC-TEC project currently can't be expressed, it is possible to expand TEC-REP to cover such cases e. g. by including primitives for surfaces described by B-spline-functions.

The reason to use a surface-based description method is simple: Every manufacturing operation always influences surfaces of an object, therefore the representation of these surfaces seems reasonable.

By using surface primitives, TEC-REP connects the basic data level with the world of symbolic reasoning. With respect to the intended deductions the surface primitives are augmented by information about the direction of material. A circular surface can represent the outer surface of a cylinder as well as a hole in some material, depending on the direction of material.

To facilitate reasoning about topological connections, the neighbourhood of surfaces is expressed in a separate primitive.



CJ(reference_point1: <vector>,
reference_point2: <vector>,
radius: <num>,
direction_of_material: [+,-])

C(reference_point: <vector>,
direction_vector: <vector>,
radius: <num>,
direction_of_material: [+,-])

Shape Tolerance DIN 7184

ST(surface_number: <num>,
tolerance_type: [SN, EN, RN, C, LD, PD],
tolerance_size: <num>)

Surface Finish

SF(surface_number: <num>,
surface_finish: [Rt, Rz, Rp, Ra,...],
value: <num>)

Figure 2. Some TEC-REP Primitives

The technological information is expressed by attributes to the surfaces. Some attributes (like surface finish or ISO-tolerances) belong to one surfaces, others connect different surfaces (e. g. length tolerances between different surfaces).

In summary, TEC-REP allows the description of every work piece we currently deal with by using a symbolic and attributed boundary representation.

4 Features and FEAT-REP - a closer look

The goal of the feature representation formalism is to allow the expression of a concrete expert's knowledge about characteristic aggregations of surfaces. When CAD/CAM experts view a workpiece, they perceive it in terms of their own expertise. These terms, called *features*, which are build upon a *syntax* (geometry and technology) and a *semantics* (e.g. skeletal plans in manufacturing or functional relations in design), provide an abstraction mechanism to facilitate the creation, manufacturing and analysis of workpieces. We define the term *feature* as a description element based on geometrical and technological data of a product which an expert in a domain associates with certain informations (see also [Klau91a] or [Klau91b]). They are firstly distinguished by their kind as

- functional features, e.g. *seat of the rolling bearing* or *O-ring groove*,
- qualitative features, e.g. *bars* or *solid workpiece*,
- geometrical (form-) features, e.g. *shoulder*, *groove* or *drilled hole*,
- atomic features, e.g. *toroidal shell*, *ring*, *shape tolerance* or *surface finish*.

and they are secondly distinguished by their application as

- design features, e.g. *crank* or *coupler*,
- manufacturing features:
  - turning features, e.g. *shoulder* or *neck*,
  - milling features, e.g. *step* or *pocket*,
  - drilling features e.g. *stepped-hole* or *lowering*,
  - ...
- ...

The domain-dependency of features can be illustrated by a comparison between features in the domain of CAPP and features in the domain of design. While the latter (which are investigated in many modern CAD-systems) represent higher-level informations about the ideas of a designer and describe things like functional relations between surfaces of different workpieces which touch each other, the former depend on

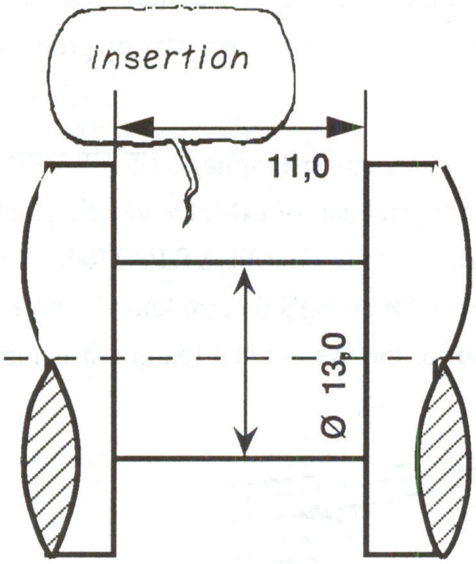


Figure 3.: Insertion

particularities of the manufacturing process and are influenced e.g. by the available manufacturing environment. In particular every feature e.g. in manufacturing will be defined by a respective expert because his area, like machines, tools or the characteristics of them, and his ideas, creativity and experience, like special tricks, are included in this definition. In this sense the features can been seen as a *language* of an expert in a domain. It is important to note that this language represents the *know-how* of the expert respectively the machine shop and that this language is an individual one ("expert in a domain" dependent). A prominent example of a such a feature in manufacturing is a insertion of certain dimensions which shall be manufactured using a certain insertion-tool. In a manufacturing environment where this tool is not available this particular insertion may be recognized as a groove or may be not recognized as a feature (figure 3).

The importance of feature recognition in manufacturing stems from the fact that each feature can be associated with knowledge about how the feature should be manufactured; this information can be used to generate a process plan. From this point of view feature recognition forms a major component of the CAD/CAM interface for CAPP [Chan90]. In our paper we concentrated on the recognition of geometrical and qualitative features; the functional features are important for design only. Working with manufacturing features means to recognize these features from the CAD data to generate a working plan. Working with design features means to construct by means of these features and to expand them to the CAD data. (cf. Klau91a)

In our paper [Klau91a] we have shown that it is possible to describe features by means of formal languages via attributed node-label-controlled graph grammars (ANLCGG's). The area of formal languages is a well established field of research and provides a powerful set of methods like parsing and knowledge about problems, their complexity and how they could be solved efficiently. The use of formal languages for feature descriptions facilitates the application of these results to the area of feature recognition and CAPP. As result ANLCGG's enables a user to define his own feature-language containing complex features and makes feature recognition a parsing process for workpiece interpretation.

To show the usability of our high-level-representation language FEAT-REP the FEAT-PATR-System was implemented as a prototypical part of PIM, by adopting a chart parser for our application in mechanical engineering. Input of our FEAT-PATR-System is a workpiece description in TEC-REP. Input is also the expert's feature knowledge about the workpiece, represented in a grammar. Output of the system is a feature-structure as shown in figure 4.

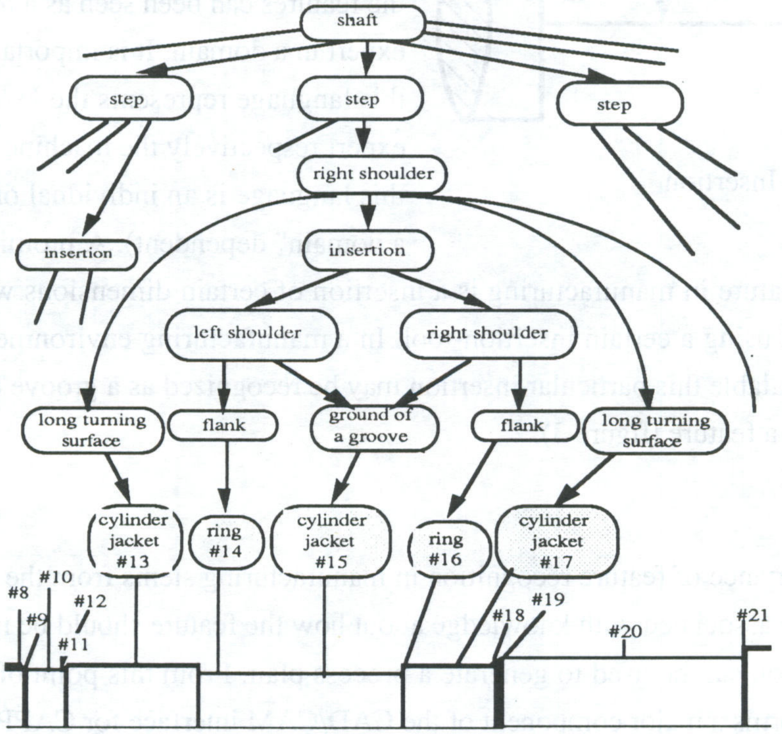


Figure 4.: Feature Structure

5 Skeletal Plans

To combine the expert's knowledge about the manufacturing process with feature structures as shown above we use skeletal plans [Richt91]|. The skeletal plan representation formalism SKEP-REP allows the expert to write down his knowledge about the process necessary for the manufacturing of his workpieces and for special parts of this workpieces (features). It also allows the expert to define how partial (skeletal) plans for special parts of workpieces (features) should be merged to complete manufacturing plans.

The idea of skeletal plans is straight forward [Frie85]: Represent knowledge about the intended solution in some partial (skeletal) plans. Find a first skeletal plan for the given goal. The plan contains some steps which are subgoals to be reached in order to solve the whole problem.

For every subgoal repeat the process until only elementary steps remain. The sequence of elementary steps is the intended plan. [Frie85]

In our domain the skeletal plans represent the expert's way of work and his knowledge. To every feature the expert associates knowledge about the manufacturing process. This may be some rather global information related to the whole workpiece, e. g. "given a workpiece of less than a certain length, use a chuck as the clamping method", as well as detailed instructions concerning small parts, e. g. "manufacture this groove using the special tool X". Such knowledge is represented in the skeletal plans. Every skeletal plan contains concrete and/or abstract information about parts of the manufacturing process or about the whole process. Every skeletal plan is associated to some feature. Feature definition and skeletal plan together represent the expert's knowledge about a certain planning task.

The concrete representation language SKEP-REP is still under development. We currently use a formalism which describes skeletal plans as shown in the following figure. A skeletal plan contains the feature or feature structure it is associated to. It then contains some context information which relates to other skeletal plans which form preconditions for the application of this particular plan. It may also contain some applicability constraints which are not expressed by the features or the context of skeletal plans. Then it contains a sequence of operations, which may result in the subroutine-like call of other skeletal plans or in the generation of concrete planning steps. In the domain of manufacturing by turning, concrete planning steps are chucking commands, cut instructions and tool selections. This steps are represented as primitives of our abstract NC-programm representation language LANCO (LAnguage for Abstract Numerical Control). Every operation may access the concrete technological and geometrical informations, especially measurements, which are represented in the TEC-REP of the surfaces which form the features associated with the skeletal plan or with the plans of the context (see above). Beside this, no information about the workpiece can be accessed. This realizes the concepts of modularity and information hiding for the skeletal plans and makes it possible to create skeletal plans for for a large bandwith of workpieces.

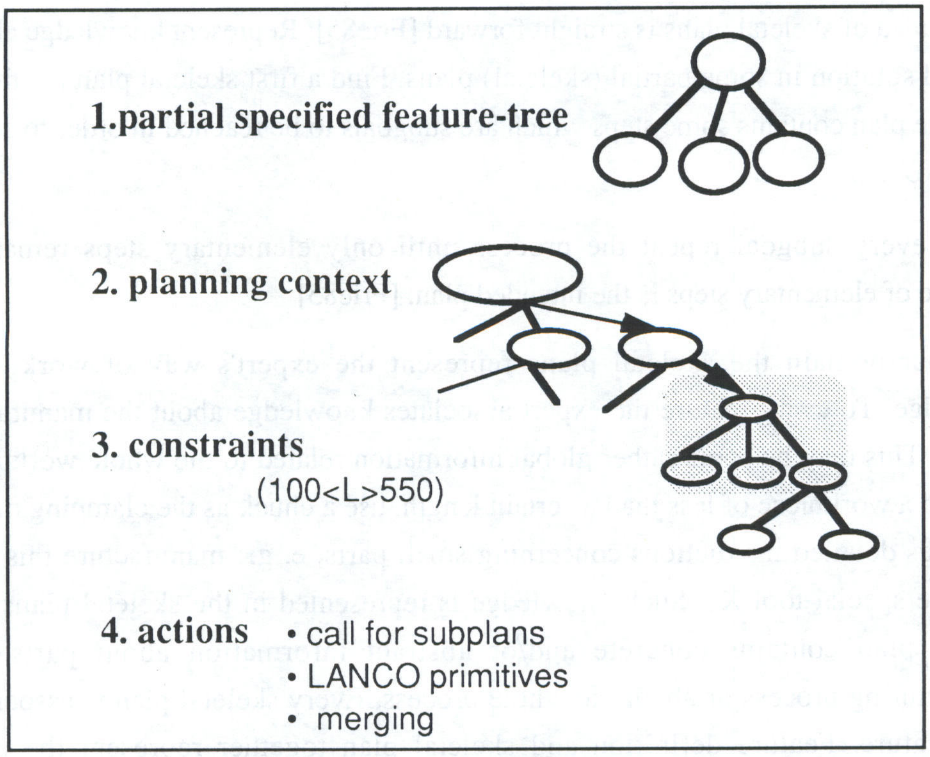


Figure 5.: Skeletal Plan Representation

Some of the operations can result in the subroutine-call of special programs for particular tasks. In our prototype, the tool selection operation uses a constraint system to find the suitable group of tools for the intended operation.

The following figure shows an example for a skeletal plan. The partial specified feature tree of this plan is a shaft which consists of crest-lstep-rtrunion. In the lower part of the figure the merging operation for the sequential planned cuts is shown.

```
(make-skp
  :special-tree
   '("shaft" shaft                                          ; partial specified feature tree
      (("crest" crest nil)
       ("lstep" lstep nil)
       ("rtrunnion" rtrunnion nil) ))
  :op-mode nil

  :constraints                                               ; list of constraints
   '(and
     (>= (Lmax *stock*) 200)
     (<= (Lmax *stock*) 600)
     (>= (Dmin *stock*) 10)
     (<= (Dmax *stock*) 150))

  :actions                                                   ; list of actions

   '((chuck shaft :kind 'in :where 'on-the-left :free-length (+ (object-length crest) 80) )
                                                                ; chucking
     (bind-global *direction* 'from-the-right)
     (plan crest)                                               ; call skeletal plan "crest"
     (chuck shaft :kind 'switch :where crest)                   ; rechucking
     (bind-global *direction* 'from-the-left)
     (center-hole shaft :kind 'create :where rtrunnion)         ; making center hole
     (center-hole shaft :kind 'move :where rtrunnion)           ; chuck with the lathe center
     (bind-local s1 (plan lstep))                               ; call skeletal plan "lstep"
   (bind-local s2 (plan rtrunnion))                             ; call skeletal plan "rtrunion"

    (merge-plans                                                ; merge the sequentialy planned
                                                                  cuts if possible
       (list (list s1 s2) :op 'roughing :kind 'lengthwise)
       (list (list s1 s2) :op 'finishing :tool-groups '(w5))
       (list (list s1 s2) :op 'recessing))
     (chuck shaft :kind 'out) ))                                ;unchucking
```

Figure 6.: A Skeletal Plan

To perform the selection and merging of the skeletal plans, a prototypical skeletal planning system was implemented as a part of our PIM system, which uses the following algorithm:

When a given workpiece description has been transformed in a feature structure according to the methods outlined in the chapter above, the skeletal plans associated with these features are found and selected according to the constraints embedded in the plans. The resulting set of skeletal plans is then merged to one final plan, and abstract variables are replaced by the concrete data of the workpiece in question. The merging of the skeletal plans is oriented on several topics: Operations using the same tool should be performed consecutively (minimalization of tool change operations). Operations in one chucking context must be performed together, minimizing the changes of chucking. Different tools belonging to a common group may be exchanged against a more general tool of this group, such that several operations using slightly different tools can be merged to one operation using only one tool. Different surfaces of a workpiece which are treated with similar operations should be grouped together.

These merging operations are supported by a hierarchical ordering of the available tools and a hierarchical grouping of the possible operations. Some heuristical approaches to skeletal plan merging are under investigation.

Figure 7 shows some output of the PIM system is shown, represented in the abstract process language LANCO. It shows the sequence of operations as well as the grouping of similarly manufactured surfaces and features which is obtained by the merging process.

```
#<Actions of Plan:
  #<CHUCK :kind IN :where ON-THE-LEFT :free-length 140 mm>
  #<ROUGHING :kind RADIAL :tool-groups (W3) :surfaces ((3) (#<Feature-Treep laneface 50>))>
  #<ROUGHING :kind LENGTHWISE :tool-groups (W2) :surfaces ((4) (#<Feature-
     Tree longturningsurface 52>))>
  #<FINISHING :kind CONTOUR :tool-groups (W5) :surfaces ((3 4) (#<Feature-
     Tree planeface 50> #<Feature-Tree longturningsurface 52>))>
  #<CHUCK :kind SWITCH :where ((3 4) (#<Feature-Tree crest 53>))>
  #<CENTER-HOLE :kind CREATE :where ((19 20 22) (#<Feature-Tree rtrunnion 8B>))>
  #<CENTER-HOLE :kind MOVE :where ((19 20 22) (#<Feature-Tree rtrunnion 8B>))>
  #<ROUGHING :kind RADIAL :tool-groups (W3) :surfaces ((10 11) (#<Feature-Tree lshoulder 66>))>
  #<ROUGHING :kind LENGTHWISE :tool-groups (W2) :surfaces ((5 6 8 9 11 12 13 15 16 17 18 19 20)
     (#<Feature-Tree lshoulder 58> #<Feature-Tree lshoulder 5E> #<Feature-Tree rshoulder 6C> #<Feature-
     Tree longturningsurface 6F> #<Feature-Tree lshoulder 77> #<Feature-Tree rshoulder 7E> #<Feature-
     Tree longturningsurface 81> #<Feature-Tree lshoulder 88>))>
  #<ROUGHING :kind RADIAL :tool-groups (W3) :surfaces ((22) (#<Feature-Tree planeface 8A>))>
  #<FINISHING :kind CONTOUR :tool-groups (W5) :surfaces ((5 6 8 9 11 12 13 18 22 19 20)
     (#<Feature-Tree lshoulder 58> #<Feature-Tree lshoulder 5E> #<Feature-Tree rshoulder 6C> #<Feature-
     Tree longturningsurface 6F> #<Feature-Tree longturningsurface 81> #<Feature-Tree planeface 8A>
     #<Feature-Tree lshoulder 88>))>
  #<FINISHING :kind CONTOUR :tool-groups (W2) :surfaces ((10 11 15 16 17)  (#<Feature-Tree lshoulder
     66> #<Feature-Tree lshoulder 77> #<Feature-Tree rshoulder 7E>))>
  #<CHUCK :kind OUT>
>
?
```

Figure 7.: Output of PIM: NC-Programm in LANCO

6 An abstract view on planning using PIM

Typical AI planning systems usually follow the methodology of STRIPS: The system searches a sequence of operators which transform a given start situation into the goal situation. Every operator is characterized by preconditions which describe the applicability of the operator and postconditions which indicate the changes of the situation resulting from the application of the operator. By standard search methods (e. g. backward chaining) it is possible to find the intended sequence of operators.

Comparing the methodology used in PIM to this, we note interesting similarities and fundamental differences: The features can be seen as aggregations of preconditions relating to geometrical/technological data of the workpiece. The workpiece description contains the description of the goal situation. The feature recognition may be seen as an efficient search method to narrow down the search space to the applicable skeletal plans. The skeletal plans then serve as indicators for the future search process. Ideally there isn't nearly any real search, as the skeletal plans determine nearly all planning steps.

In summary, the expert's knowledge, represented in features and skeletal plans, is employed to drastically reduce the search space of the planning task.

The planning task itself - to bridge the gap from CAD to NC - is exchanged against some transformation steps from between representation languages. On the level of features and skeletal plans, the gap is bridged by associations representing expert's knowledge. The found skeletal plans are then refined using the concrete data, such that the intended code can be generated. So the planning task boils down to an sequence of abstraction, association and refinement, as illustrated in figure 8, hereby eliminating the need for undirected and inefficient search.

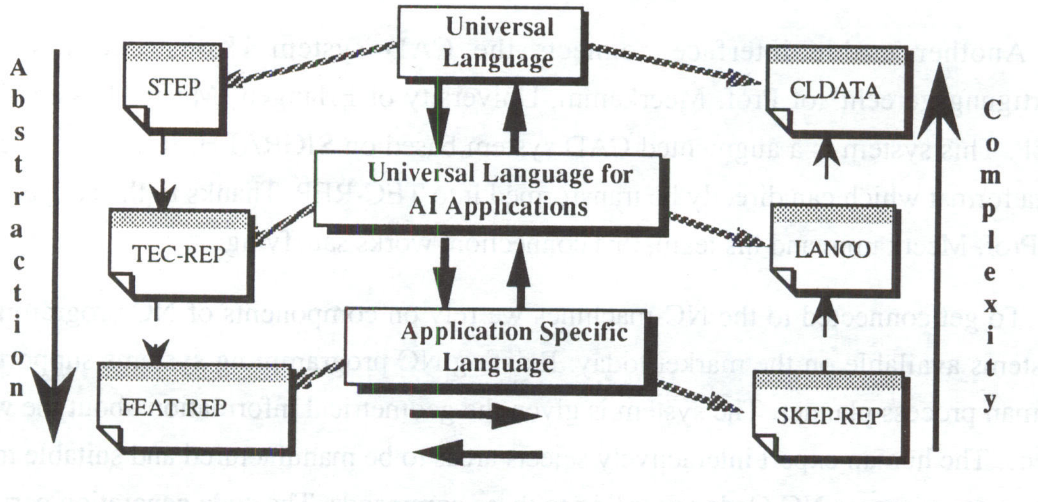


Figure 8.: Abstraction levels of PIM (Planning In Manufacturing)

Beside this it must be remembered that the main advantage of the PIM approach lies in the explicit representation of the special knowledge of an expert in his manufacturing environment. In contrast to systems which employ only general rules this approach solves the problem of the very special and environment-dependend knowledge necessary to create good plans, as motivated in the first chapter.

Intensive talks with many domain experts proved that this approach in fact resembles the way a human expert thinks, which should lead to a high acceptance of such a system by the expert.

7 Connections to the real world

Every CAPP-System serving any useful purpose must be embedded in the existing CA*-world. It has to accept the workpiece description from CAD and its output will be fed into NC machines which manufacture the workpiece. The PIM system fulfils this requirement using interfaces to CAD and NC programming systems.

The interface to the CAD world transforms the necessary geometrical/technological information about the workpiece from the CAD data into our TEC-REP. The forthcoming ISO-standard STEP [Grab 89] [Bern90] promises to provide a data exchange format covering all necessary information and providing a system-independent interface. While currently only some prototypes of CAD systems are able to produce STEP files, this will certainly change in the near future. Consequently, a prototypical processor was developed to create TEC-REP files out of a given STEP data file using the information of the geometry, topology and technology models of STEP.

Another usable interface connects the CAD system "Konstruktionssystem Fertigungsgerecht" of Prof. Meerkamm, University of Erlangen [Meer91], with TEC-REP. This system is a augmented CAD system based on SIGRAPH. It uses an internal data format which can directly be transformed into TEC-REP. Thanks to the cooperation of Prof. Meerkamm and his team, this connection works satisfying.

To get connected to the NC-machines we rely on components of NC programming systems available on the market today. Existing NC programming systems support the human process planner. The system is given the geometrical information about the work piece. The human expert interactively selects areas to be manufactured and suitable tools. The system creates NC-Code according to these commands. The code generation part of a NC programming system doesn't rely on human experts giving the commands,t he output of a planning system like PIM can serve as a command sequence as well. So a commercially available NC programming system is connected to PIM as follows:

The output of the PIM system is compiled into the command language of the NC programming system.Then, the NC programming system can generate CLDATA Code as well as machine specific NC-Code, without any further human interaction.

8 Some tools to support our approach

The basic idea behind the PIM system is the explicit representation of a concrete expert's knowledge in his given manufacturing environment in order to closely mimic the expert's problem solving behavior. This methodology leads to special requirements in the area of knowledge acquisition as well as in the area of AI reasoning methods.

According to the intended use of the PIM system, a lot of knowledge acquisition must be performed in the field. In any given manufacturing environment, the expert's knowledge must be acquired and represented separately. This is especially important for any proprietary knowledge and special manufacturing tricks of a factory. When the manufacturing environment changes during the life time of the system, the adequate knowledge must be acquired and represented again in order to adapt to new possibilities. (New tools can lead to new manufacturing methods and consequently to new manufacturing features). The acquisition group of the ARC-TEC project provides tools to support the necessary knowledge acquisition for every step in the systems life cycle [Schm91].

The compilation group of the ARC-TEC project deals with suitable and efficient reasoning mechanisms for the represented knowledge. Taxonomies are handled using the terminological representation language TAXON [Baad91] This extension of a KL-ONE like language can be used to represent the hierarchical dependencies, e. g. a hierarchy of manufacturing tools. Constraints arising in the area can be tackled using the tool CONTAX, which couples a constraint propagation system with the taxonomies. The integrated forward/backward reasoning system FORWARD/RELFUN is suitable for reasoning about the preconditions of the skeletal plans.

9 Conclusion

The observation of human expert's problem-solving behavior resulted in a model of process planning which supports a knowlegde-based approach to CAPP. Based on technological/geometrical information about the workpiece, higher-level features are defined and associated with skeletal plans.

Special languages for a adequate representation of the necessary knowledge on the different abstraction levels were presented. The transformation and interpretation steps between the different languages have been implemented and form the planning system PIM. This system creates a production plan to a given workpiece by performing a sequence of abstraction, selection and refinement.

The approach pursued in the PIM system closely mimics the expert's problem solving behavior. The resulting system is especially tailored to a concrete manufacturing environment and uses the expert's knowledge optimally. This should lead to good quality of the produced plans and to high acceptance of the system. Positive comments of many domain experts support this claim.

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