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Computer-Aided Process Planning for Machining

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Abstract

This chapter presents an overview of the research work in computer-aided process planning (CAPP) during the past 2 decades. This has been driven primarily by the need to automate the mapping of design information and intent from computer-aided design (CAD) systems to instructions for driving automated manufacturing equipment. While the concept of CAPP extends over all manufacturing domains, we summarize those developments primarily in the machining domain. As part of CAPP research, we also discuss developments in the area of feature recognition. Features are fast becoming the mechanism through which higher level design information is embodied and manipulated within the computer-aided engineering (CAE) environment. Feature recognition is one mechanism by which this higher level of abstraction is constructed and related to the underlying geometry. Finally, we briefly introduce a new area of research in CAPP, parallel machining.

2.1 Introduction

The past decade has seen an explosion in the use of computers throughout all engineering diciplines. This is particularly true in the activities that span the life cycle of discrete product development. Commercial viability of computer-based tools has occurred at either end of the product life cycle, i.e., in product design and in manufacturing. In product design, previously expensive CAD systems are now affordable and run on ever cheaper and more computationally powerful PCs, which makes this technology more widely accessible to an evergrowing number of users. In addition, the sophistication of these systems has increased dramatically. Whereas the initial first-generation CAD system was primarily concerned with wireframe modeling and automated drafting, current third-generation systems are incorporating features technology built on top of powerful geometric/solid modeling engines (second-generation systems).

As explosive as the CAD side of product development has been, so has that in manufacturing automation. With the advent of cheaper computers and controllers, an increasing percentage of machines used in the modern factory is software controlled and interconnected through networks. This greatly reduces the length of time during which a machine tool or robot can theoretically be reprogrammed for a new task, thus increasing productivity. Practically, these increases are yet to be realized because of the lead time required to convert design information into programs to drive these machines. Computer-aided process planning (CAPP) systems enable shorter lead times and enhanced productivity in the automated factory.

In the following sections, we discuss research developments in CAPP systems during the past 2 decades. While much research has been done, commercialization of this technology is yet to be realized in the same way that other CAE technologies have experienced.

2.2 What Is Computer-Aided Process Planning (CAPP)?

In this section we introduce the topic of CAPP, and review important components of this technology.

Chang and Wysk (1985) define process planning as "machining processes and parameters that are to be used to convert (machine) a workpiece from its initial form to a final form predetermined from an engineering drawing." Implicit in their definition is the selection of machining resources (machine and cutting tools), the specification of setups and fixturing, and the generation of operation sequences and numerical control (NC) code. Traditionally, the task of process planning is performed by a human process planner with acquired expertise in machining practices who determines from a part's engineering drawings what the machining requirements are.

Manual process planning has many drawbacks. In particular, it is a slow, repetitive task that is prone to error. With industry's emphasis on automation for improved productivity and quality, computerized CAD and computer-aided manufacturing (CAM) systems which generate the data for driving computer numerical control (CNC) machine tools, are the state-of-the-art. Manual process planning in this context is a bottleneck to the information flow between design and manufacturing.

CAPP is the use of computerized software and hardware systems for automating the process planning task. The objective is to increase productivity and quality by improving the speed and accuracy of process planning through automation of as many manual tasks as possible. CAPP will increase automation and promote integration among the following tasks:

1. Recognition of machining features and the construction of their associated machining volumes from a geometric CAD model of the part and workpiece
2. Mapping machining volumes to machining operations
3. Assigning operations to cutting tools
4. Determining setups and fixturing

5. Selecting suitable machine tools
6. Generating cost-effective machining sequences
7. Determining the machining parameters for each operation
8. Generating cutter location data and finally NC machine code

Traditionally, CAPP has been approached in two ways. These two approaches are variant process planning and generative process planning. In the following section we discuss these and other issues in a review of work in this field.

2.3 Review of CAPP Systems

The immense body of work done in the field of CAPP makes it impossible to discuss each development in detail within the confines of this chapter. We, therefore, direct the reader to Alting and Zhang (1989), CAM-I (1989), and Kiritsis (1995) for detailed surveys of the state-of-the-art in CAPP. Eversheim and Schneewind (1993) and ElMaraghy (1993) provide good perspectives on the future developments of CAPP. It is worth mentioning that although the surveys by Alting and Zhang (1989) and CAM-I (1989) are over 12 years old, they came at a time when most of the basic foundation for CAPP system development had already been laid. Although new researchers have entered the field, these surveys still provide valuable insight to the problem. Kiritsis (1995) provides a later survey that focuses on systems that are knowledge based. He also classifies the feature recognition approach that is used for each reviewed CAPP system. The perspectives proposed by Eversheim et al. (1993) and ElMaraghy (1993) are directed toward a second generation of CAPP systems. The characteristics of these second generation systems are summarized in Section 2.5.

Figure 2.1 is a chronology of CAPP system developments through the 1980s until 1995, showing some of the more well-known contributions. In addition to indicating the year when each initiative began, the figure also lists the characteristics of each system. These characteristics include among others, the planning methodology adopted and the planning domain that is targeted. In the following sections we discuss a subset of the most important characteristics.

2.3.1 Variant Planning

The variant planning approach was the first to be adopted by CAPP system developers. This approach, as the name implies, creates a process plan as a variant of an existing plan. The most common technique used to implement this approach is group technology (GT). GT uses similarities between parts to classify them into part families. When applied to machining process planning, a part family consists of a set of parts that have similar machining requirements. In addition to part family classes, two other ingredients are necessary for variant process planning: a coding scheme for describing parts, and a generic process plan for each part family.

Whenever a process plan is needed for a new part, the part in question is mapped to a part code. This code is then compared with a code associated with each part family class. If a match is found, the plan for the matched family is retrieved. It is then modified to suit the new part.

The variant approach has obvious disadvantages. The most glaring is the dependence for success on the existence of a family with which a match can be made. This means that new parts with significantly different characteristics than any found in the database must be planned from scratch. Another major disadvantage of the variant approach is the cost involved in creating and maintaining databases for the part families. Due to these problems, variant systems are normally adopted only when a well-defined part family class structure exists, and it is expected that new parts will generally conform closely to the characteristics of these classes.

Variant systems developed in-house have been widely implemented throughout industry. Examples include CAPP, (Link, 1976) GENPLAN, (Tulkoff, 1981), and GTWORK (Joshi et al., 1994).

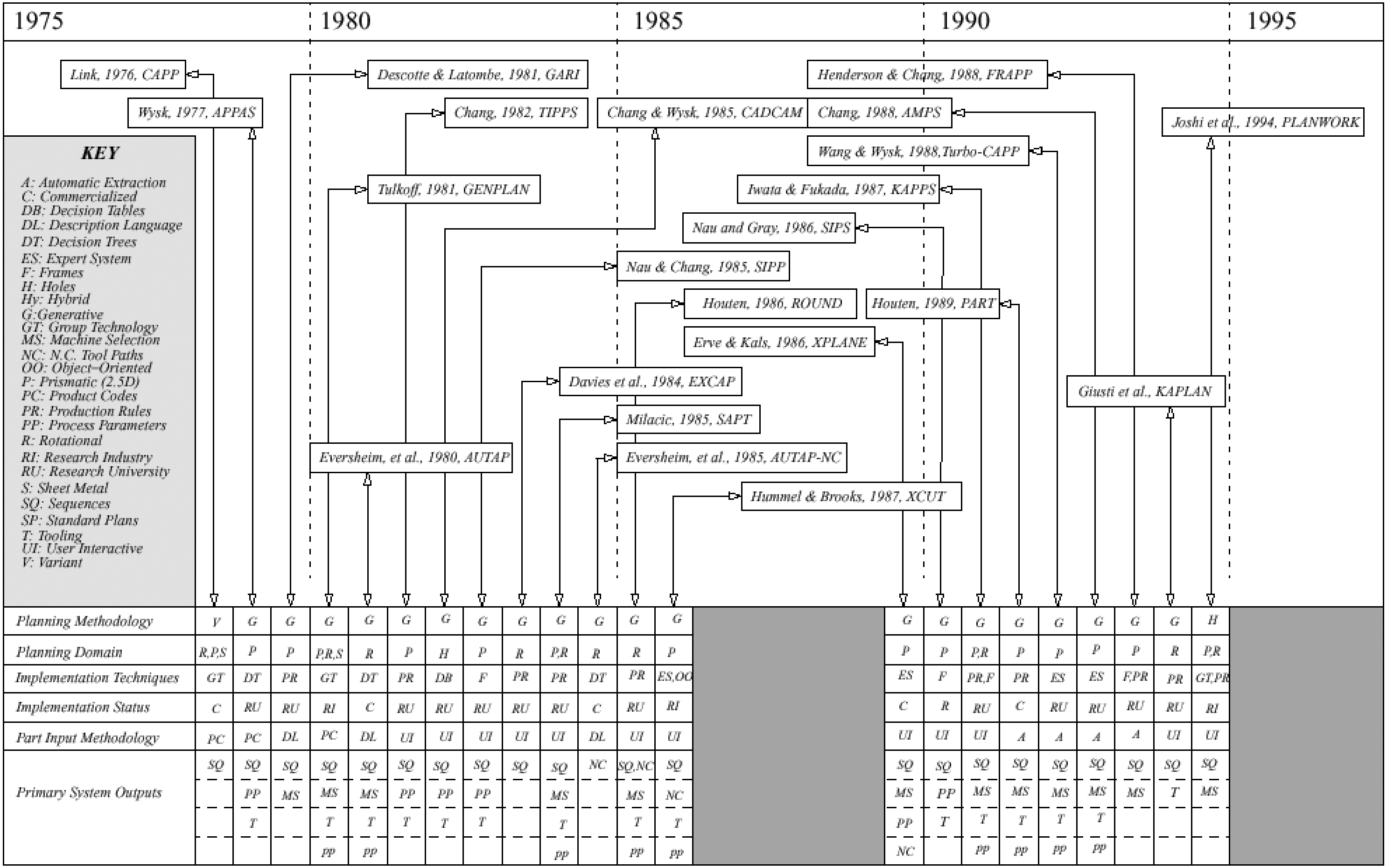

FIGURE 2.1 CAPP system development chronology.

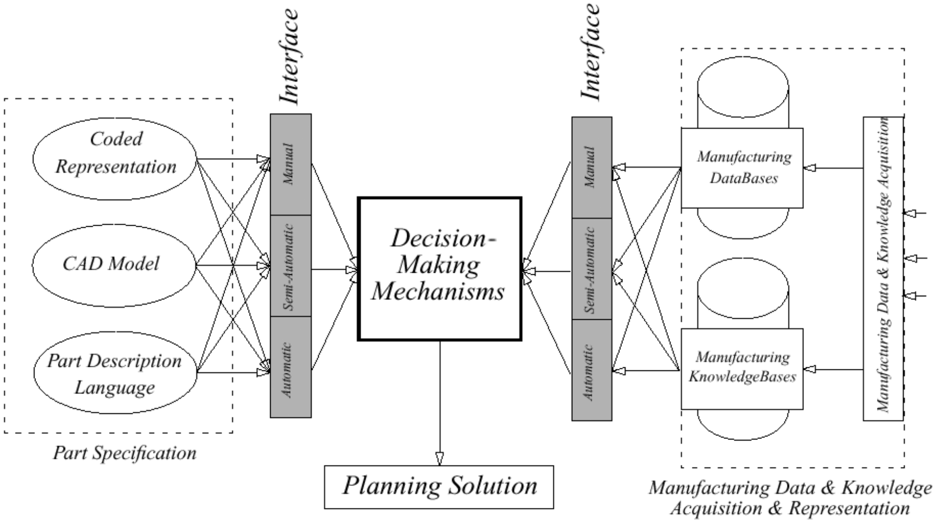

FIGURE 2.2 Components of a generative CAPP system.

2.3.2 Generative Planning

Generative planning creates unique process plans from scratch for each new part, utilizing algorithmic techniques, process knowledge, process data, and the geometric and technological specifications of the part. In contrast to the variant approach, generative planning does not use a generic family plan as the starting point. Experiential knowledge is applied through the use of techniques such as decision tables, decision trees, or production rules which can be customized to fit specific planning environments. The key components of a generative CAPP system are illustrated in Figure 2.2. They are

- *Part Specification Input*: See Section 2.3.7.
- *Manufacturing Data and Knowledge Acquisition and Representation:* In the machining domain this refers to the data and knowledge that are commonly applied by human process planners in planning machining operations. In this context, examples of manufacturing data are the machining process parameters stored in a database or derived from formulae constructed from machinability experiments. Examples of machining knowledge are the rules that match machining requirements based on part specifications to process capabilities.
- *Decision-Making Mechanisms:* These are the techniques used to generate a process plan given the part specifications and the available manufacturing data and knowledge. Examples of these mechanisms include hard-coded procedural algorithms, decision trees and tables, and production rules. The actual decision-making mechanism is likely to be a hybrid combination of different types of reasoning mechanisms.

Generative process planning systems are not necessarily fully automatic. Chang (1990) used the term automatic process planning to define systems with (1) an automated CAD interface, and (2) a complete and intelligent planning mechanism. Because these are the two major high-level tasks in planning, these systems eliminate human decision making. The current state-of-the-art is such that no CAPP system, either research or commercial, can claim to be fully automatic.

A major advantage of generative CAPP systems over variant systems is that they can provide a planning solution for a part for which no explicit manufacturing history exists, i.e., no variant of the part has an existing plan which may be retrieved and modified. Another advantage is the generation of more consistent process plans. While these advantages seem to weigh heavily in favor of generative planning solutions, the practical problems to be overcome are formidable. The computerization of manufacturing knowledge (its acquisition, representation, and utilization), in particular, is difficult. A high level of expertise is currently required to build and maintain knowledge bases. Cost effectiveness and confidence in such systems are not yet at a state where commercialization is viable. Examples of generative CAPP systems are APPAS (Wysk, 1977),TIPPS (Chang, 1982), EXCAP (Davies et al., 1988), SIPS (Nau and Gray, 1986), XPLANE (Erve and Kals, 1986) XCUT (Hummel and Brooks, 1986; 1988; Brooks et al., 1987), and PART (Houten and Erve, 1988; 1989a; 1989b; Houten et al., 1990).

2.3.3 Hybrid Planning

While fully generative process planning is the goal of CAPP system development, in the interim, systems that combine the variant and generative planning approaches are useful. We refer to these as hybrid planners. Another term used to refer to this approach is semi-generative plannign (Alting and Zhang, 1989). A hybrid planner, for example, might use a variant, GT-based approach to retrieve an existing process plan, and generative techniques for modifying this plan to suit the new part (Joshi et al., 1994).

One important aspect of hybrid planning is user interaction. As generative CAPP systems become more and more automatic, the amount of work a process planner needs to do will decrease. However, this trend should not lead to a process planning system that removes the human planner from the roles of arbitrator and editor. The human planner should always have the ability to modify and influence the CAPP system's decisions. This leads to a hybrid planning approach where two parallel planning streams exist. The first utilizes generative planning techniques, and the second a user-interaction approach. User interaction acts either to bypass generative planning functions or becomes part of feedback loops in an evaluate-and-update cycle. In this way, the user always has control over the planner and makes the final decisions when conflicts arise that cannot be resolved automatically.

2.3.4 Artificial Intelligence (AI) Approaches

Since the early 1980s, AI techniques have found widespread application in CAPP work. They have been applied both at the feature recognition stage and in capturing best machining practices for the purposes of operation selection and sequencing, resource selection, and process plan evaluation. Expert systems have been the main AI tool used in CAPP work. These systems combine domain data, knowledge (rules), and an inference mechanism for drawing conclusions about a planning problem. Expert systems are based on nonprocedural programming in contrast to the procedural approach of more conventional programming languages such as Basic, Fortran, or C. This makes them especially suited for domains where algorithms are difficult to structure and where high uncertainty exists.

Knowledge representation schemes used in expert systems include production rules, frames, semantic nets, predicate logic, and neural networks. Of these, the most commonly used are production rules and frames. CAPP systems that use production rules include GARI (Descotte and Latombe, 1981) (one of the first AI-based CAPP systems), TIPPS (Chang, 1982), SAPT (Milacic, 1985; 1988), XCUT (Hummel and Brooks, 1986), Turbo-CAPP (Wang and Wysk, 1987), Hi-Mapp (Berenji and Khoshnevis, 1986), and FRAPP (Henderson and Chang, 1988). Systems that use frames include SIPP (Nau and Gray, 1986), Hi-Mapp (Berenji and Khoshnevis, 1986), FRAPP (Henderson and Chang, 1988) and QTC (Chang et al., 1988).

2.3.5 Object-Oriented Approaches

Object-oriented programming is often associated with artificial intelligence. They provide a technique by which data and methods can be encapsulated within an object. Encapsulation masks the inner workings of the object behind an interface through which the objects communicate with each other and the rest of the world. Inheritance allows objects to be ordered hierarchically such that they inherit data and methods from their ancestors.

One of the most powerful features of object-oriented programming is the ability to separate the calling program or application from the inner workings of objects. The calling program interacts with objects through the use of message handlers (member functions in the case of C++). This interface allows objects to be changed without the need to modify the application program in which the objects are used. This is particularly useful in situations where objects are changing or evolving, as is usually the case in the CAPP domain.

Object-oriented programming has been integrated into expert system shells. CLIPS™ (C Language Integrated Production System* (Giarrantano and Riley, 1989) is an example of this. COOL™ (CLIPS' Object-Oriented Language) allows the knowledge engineer to represent data as objects and manipulate these objects within production rules. This is a great help in structuring and managing the knowledge base. XCUT (Hummel and Brooks, 1986) is an example of a CAPP system which uses a rule-based expert system with an embedded object-oriented language. Other researchers who have utilized the object-oriented paradigm include Turner and Anderson (1988), Lee et al. (1991), and Yut and Chang (1994).

2.3.6 Part Geometry

Almost all CAPP research work in the machining domain focuses on either rotational or prismatic (2.5D milled) part geometries. Systems that generate plans for rotational parts include MICROPLAN (Philips et al., 1986), DMAP (Wong et al., 1986), ROUND (Houten, 1986), and EXCAP (Davies et al., 1988). Examples of systems that generate plans for prismatic parts include GARI (Descotte and Latombe, 1981), TIPPS (Chang, 1982) SAPT (Milacic, 1985) Hi-Mapp (Berenji and Khoshnevis, 1986), SIPS (Nau and Gray, 1986), XCUT (Brooks et al., 1987) and PART (Houten and Erve, 1988; 1989a; 1989b; Houten et al., 1990).

2.3.7 Part Specification Input

The front end to a generative planning system is designed to input the part specification. Various approaches have been adopted for this step. Some approaches use coding schemes similar to those found in many variant planning systems to describe the part. One example is that adopted by Wysk (1977) as part of the APPAS generative planning system. The coding scheme in this work is called COFORM (Rose, 1977) and is used to generate a coded description of each individual machined surface of a part. The surface's coded attributes are subsequently used to drive process selection in the generative planner.

Another approach to part specification input is through the use of a part description language which translates the basic part geometry into a higher level format that can be used by the process planning system. Technological information (surface finishes, tolerances) also can be included. Examples of this approach to part input can be found in GARI (Descotte and Latombe, 1981) and AUTAP-NC (Eversheim and Holtz, 1982). One of the problems encountered in using part description languages and codes in the earlier systems was that the information for each part needed to be prepared manually. This was both time consuming and prone to error. With CAD systems, it is now possible to write a translator to automatically or interactively create the part description file.

The widespread use of solid modeling in CAD now makes this the preferred choice for part specification input. However, because part modeling and planning tools (e.g., expert system shells) generally are not designed to work as an integrated environment, the information within CAD

*CLIPS™ and COOL™ are components of an expert system shell developed at the Software Technology Branch of the Lyndon B. Johnson Space Center.

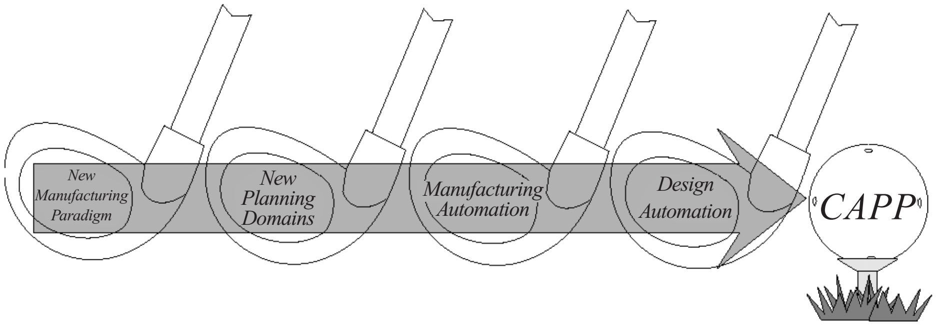

FIGURE 2.3 Drivers of CAPP.

models must still be translated to some representation within the planning environment (e.g., frame or object instances). A truly integrated system will allow the planning mechanisms (rules or methods) to directly interrogate the CAD model.

2.4 Drivers of CAPP System Development

In the previous section we reviewed work in CAPP. In this section we briefly discuss the drivers of CAPP system development. This discussion shows that continual advances in design and manufacturing automation, the emergence of new planning domains, and ever-changing market conditions call for new and improved CAPP tools. As illustrated in Figure 2.3, developments in CAPP are driven primarily by

- Design automation
- Manufacturing automation
- Extension of planning domains; new planning domains
- Market conditions

2.4.1 Design Automation

Design automation closely parallels advances in computer hardware and software. In particular, design automation is driven by advances in CAD. The growth of CAD software development remained strong throughout the 1990s. The following trends are largely responsible for this growth:

- More computing power for less cost
- The use of solid modeling as an integral part of CAD systems
- CAD software migration from UNIX systems to PC platforms
- Feature-based CAD systems

The result of these trends is that powerful CAD systems are now available to a much wider range of end-users than ever before. With a large proportion of CAD systems being links in the production cycle, a corresponding increase in the need to convert CAD product models quickly and easily into manufacturing data exists.

2.4.2 Manufacturing Automation

As with design automation, trends in manufacturing automation are geared toward improving the speed, efficiency, predictability, reliability, and quality of manufacturing processes. Machining systems in particular are an example of this trend. The mill/turn is one machining system that represents the state-of-the-art in manufacturing automation. At the same time, severe restrictions exist on the utilization of this type of complex machining system because of the lack of automated process planning tools. This work is, in fact, an example of how advances in manufacturing automation are driving CAPP system development.

2.4.3 Extension of Planning Domains; New Planning Domains

Developments in CAPP are always driven by the introduction of new planning domains and the extension of old ones. Most of the work to date in CAPP has focused on process planning for machining. New planning domains, on the other hand, arise when new processes are created. An example of a new process is layered manufacturing. This process creates parts a layer or slice at a time. Researchers are looking at a broad range of issues which can be regarded as process planning for this new domain. They include adaptive slicing, locating the optimal part orientation, and the generation of support structures.

2.4.4 Market Conditions

What is eventually manufactured is dictated to a large extent by demand. The market conditions that reflect demand usher in new manufacturing paradigms from time to time. These paradigm shifts are the manufacturing sector adapting to market forces so as to remain viable and competitive. According to analysts (e.g., Pine, 1993), the mass production system that characterized manufacturing from the 1960s through the 1980s is giving way to a new paradigm, one of mass customization, in which traditional, standardized products are replaced by those customized to individual consumer needs and preferences. This leads to the fragmentation of homogeneous markets with subsequent reductions in product development time and overall life cycles.

CAPP is a crucial piece of the puzzle in creating a manufacturing environment that is responsive to mass customization. An ability to create customizable CAD models (using features and parametric modeling, for example) needs to be matched with an ability to generate manufacturing data for those models just as quickly. Without efficient CAPP systems for mapping design specifications to manufacturing instructions, design and manufacturing environments that are separately responsive to customized production are largely unresponsive when integrated.

2.4.5 Summary of Drivers

From the above discussion, the following can be said about the drivers of CAPP system development:

- Advances in design and manufacturing automation continue to call for better CAPP tools.
- CAPP development is needed for extensions to existing domains (machining) and to provide automation for new domains.
- The move toward mass customization in manufacturing requires CAPP systems that are compatible with tools in design and manufacturing environments that are responsive to customized product development.

Figure 2.4 illustrates the view of CAPP as both an interface and a bottleneck between CAD and CAM. While it is likely that CAPP will remain the weakest of the three, the drivers we have discussed are challenging CAPP system developers to make the bottleneck as wide as possible.

2.5 Characteristics of CAPP Systems

In the previous section we looked at the drivers of CAPP system development. In this section we present a set of CAPP system characteristics that are required if these systems are to become viable, integrated parts of production environments. We do this by first presenting our perspectives on

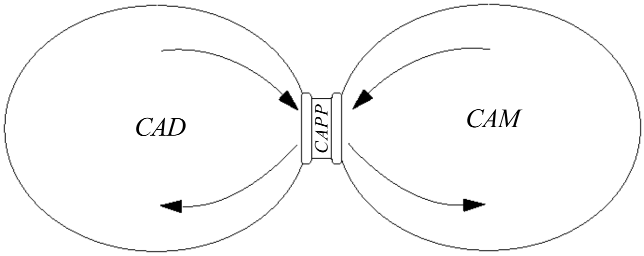

FIGURE 2.4 CAPP bottleneck between CAD and CAM.

CAPP systems based on experiences from research in the field. These perspectives along with their relevance to the key characteristics of CAPP systems are presented in Table 2.1.

A major problem that has affected the evolution of CAPP systems toward commercialization is that many systems have been implemented using a prototype philosophy. With this approach a tendency exists to neglect important practical concerns which greatly affect the nature of the conceptual and implemented models. Because the ultimate goal is to provide an end-user with a practical CAPP solution, these concerns must be addressed if these systems are to become commercially viable. The perspectives presented in Table 2.1 address many of these concerns.

Table 2.2 brings this discussion full circle. It summarizes the characteristics presented in Table 2.1 (plus a few others) and indicates the effect(s) of the characteristic. These effects in turn address the perspectives presented in Table 2.1.

2.6 Integrating CAD with CAPP: Feature Extraction

A considerable amount of research effort has been invested in integrating CAPP with CAD. A major component of this task is the extraction of machining features from a CAD representation of the product. This is an essential step in improving the speed at which design information is converted into manufacturing instructions during process planning. This section reviews some of the important research contributions in this field.

2.6.1 What Are Features?

The term feature is now commonly used in engineering jargon. The first use of the term was, however, in the context of process planning. One of the earliest definitions of a feature can be found in CAM-I:41 A specific geometric configuration formed on the surface, edge, or corner of a workpiece.

The use of the term workpiece in the definition shows the relation to the machining domain. Other researchers who have linked their definition of a feature to the manufacturing domain include CAM-I (1986), Chang et al. (1988), Henderson (1984), Hummel and Brooks (1986), Turner and Anderson (1988), and Vandenbrande (1990).

Since its inception in the process planning domain features, technology has evolved to encompass a much broader range of definitions. The following terms are examples of some definitions that are relevant to this work (for a more comprehensive list of feature terms, see Shah (1991):

Form Feature: First used in the process planning domain. Form features are defined based on their geometry and not their function. Examples of form features include holes, slots, steps, and pockets.

Manufacturing Feature: A feature that is meaningful within a manufacturing domain. Although the machining domain is the most common, researchers also have looked at other domains including features in sheet metal manufacture.

Machining Feature: A feature that is generated by a machining process.

Volumetric Feature: A volumetric feature consists of a connected solid entity that corresponds to a removal (sub-) volume for a particular manufacturing process. This definition is relevant to the machining domain.

Surface Feature: A surface feature is a collection of workpiece faces that result from machining (i.e., subtracting) a volumetric feature (Vandenbrande, 1990).

Precision Feature: This may refer to reference or datum surfaces from which dimensions or tolerances are specified, or to the actual dimensions or tolerances themselves.

Many different ways of using the concept of features exist in engineering design and manufacture. Although a number of attempts have been made to create feature taxonomies, e.g., CAM-I (1986), no standard has yet been adopted by the research community. This is problematic because the lack of standardization works against integration. For example, having a standard set of design and manufacturing features would allow researchers to develop generic methodologies for mapping between the two domains. This would help to integrate CAPP with feature-based CAD.

For machining process planning, machining features are of primary interest. Figure 2.5 illustrates how they are related to the broader view of features. Machining features are just one of many different types of manufacturing features as can be seen from Figure 2.5(a). Other types of manufacturing features include casting, welding, and sheet metal features. Manufacturing features themselves are a subclass of the basic feature class. Other subclasses at the same level include design features and assembly features.

Two ways of representing a machining feature are illustrated in Figure 2.5(b). The first representation defines the feature by the machined surfaces that are left on the part after the machining process, a slotting operation in this example. The second representation defines the feature by the actual volume that is removed by the machining process, referred to as a machining volume. The two representations are, in fact, interdependent; by removing a machining volume associated with a machining feature, its machined surfaces are generated. The machined surfaces representation is, however, more general because as indicated in the figure, more than one machinable volume may generate the same machined surfaces (e.g., S1 or S1').

2.6.2 Feature Recognition

The area of feature extraction has received much attention over the past 2 decades. We discuss in the following sections relevant developments that have taken place in the field, including a chronology of feature extraction work since 1980 when research in this field was first published. This chronology classifies the feature extraction methodologies into one of several categories. The more important contributions are discussed.

The purpose of feature recognition in the context of machining process planning is to identify machining features in a CAD model. Research work in feature recognition can be classified into the following areas:

- Volume decomposition
- Alternating sums of volume
- Graph-based recognition
- Syntactic pattern recognition
- Knowledge-based feature recognition
- User-interactive recognition
- Recognition from CSG representations
- Recognition from 2D drawings
- Hybrid feature recognition
- Recognition of alternate feature sets

TABLE 2.1 Perspectives on CAPP System Characteristics

		CAPP System Characteristics									
Perspective	Comments	User Friendly	Customizable	Robust	Extendable	Complete	Adaptable	Integratable	Teachable	Modular	Efficient
1. An ability to generate, compare, and record multiple process plans to a given part input.	The user should be able to generate multiple feasible mappings of the part to manufacturing operation sets. This is facilitated by the paradigms for interpreting the part and applying machining practices.					•					
2. An ability to learn in a quick and efficient way that is controlled by the end-user.	Two areas where learning capabilities can be utilized are in the part interpretation stage (matching volume extraction) and in the application of manufacturing practice rules.		•		•				•		
3. The system should evolve during use to provide planning that is adapted to the application.	Due to this feature, the unique quality of a CAPP system becomes the information it has acquired during use within a particular environment. This will obviously vary from user to user. The “local knowledge” makes the system more user friendly after it has fully evolved.		•				•				
4. CAPP systems should demonstrate definite time savings and provide consistently equivalent or better plans than those generated by human planners.	This implies that the system should be easy to use and can perform computationally in a manner that is acceptable to the planner. It is worth noting that most systems in use today demonstrate savings of less than 15% over manually prepared plans.			•							•
5. The CAPP system should assimilate information from various stages of the product life cycle, most importantly from the shop floor.	Process plans must often be modified by shop-floor personnel during a test period when the part is brought into production. The reasoning used to make these changes is often lost. Integrating this knowledge into the accumulated knowledge within the process planning tools can lead to future plans utilizing this knowledge at the planning stage.				•			•	•		

6. The philosophy of a CAPP system as a black-box is unacceptable to most end-users.	To most process planners the inability to understand how a solution is generated and to control and influence the generation, leads to skepticism. The more the system is understood and tailored by those who use it, the more accepted it will be.	•	•								
7. The CAPP system should be independent of any specific design or manufacturing system.	The purpose of this is to make the system usable by the largest range of end-users who as a group may have a wide variety of CAD/CAM systems which must be integrated with process planning.							•			
8. CAPP systems should provide tools which aid synthesis and analysis in addition to tools which seek to automate and simulate.	While automation may promote planning efficiency, planning diversity comes from allowing the end-user to investigate a wide range of feasible planning solutions. Efficient synthesis and analysis tools give impetus to the planner to explore new approaches to machining.	•				•					•
9. CAPP systems should be more holistic in their approach to planning.	CAPP system research and commercialization have focused primarily on machining processes even though few mechanical parts are produced solely by machining. A holistic system that can combine many processes within one planning environment generates more complete solutions.				•	•					
10. CAPP systems should support planing on different levels.	There are many activities for which an initial, nondetailed (high-level) process plan might be useful: bidding for jobs, and for equipment procurement and facility planning.					•					
11. The CAPP system should be cost effective to purchase, operate, and maintain.	Because much manufacturing work is out-sourced today, CAPP systems must be affordable to smaller manufacturers.		•							•	

TABLE 2.2 CAPP System Characteristics and Their Effects

Characteristic	Effects
Complete	• Provides a complete manufacturing solution for the part in question. • Meets all the end-user's requirements. • Facilitates the generation of multiple solutions.
Extendable	• New technologies can be merged into the system. • The system can be extended by the end-user or a third-party software developer.
Adaptable	• The system can be used by many different types of end-users.
User Inclusive	• Utilizes human expertise and computer efficiency in correct proportions. • Promotes synthesis and analysis in addition to automation and simulation.
User Friendly	• Easy to implement and maintain. • Easy to use.
Teachable	• Allows the expertise of the end-user to be incorporated into the system. • The system can act as an archiving tool for the end-user's expertise. • The system can be used to train new process planners.
Customizable	• The system (and its cost) can be tailored to the end-user's requirements.
Modular	• Facilitates extendability, adaptability, customizability, and cost effectiveness.
Robust	• Provides consistently "correct" (by the end-user's standard) solutions. • Reduces human error.
Efficient	• Solutions are generated in a more timely fashion than by conventional planning. • The work load for a process planner generating a solution is reduced.
Integratable	• Implementation is not computer hardware or software specific.
Cost Effective	• The system in a customized form suits the budget of a wide range of end-users.

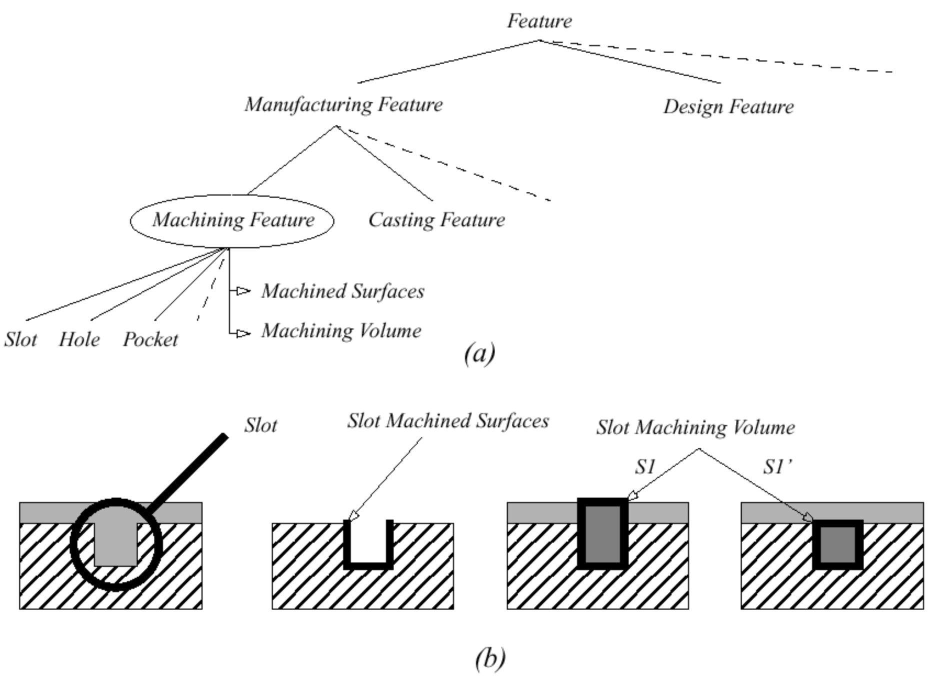

FIGURE 2.5 Machining features.

Figure 2.6 presents a chronology of feature recognition work during the past 2 decades. The figure shows the year in which the research was published as well as the category (from above) into which the work falls. It can be seen from the figure that graph-based recognition, syntactic pattern recognition and knowledge-based approaches have received the widest attention. In the following sections, some of the categories mentioned above are discussed.

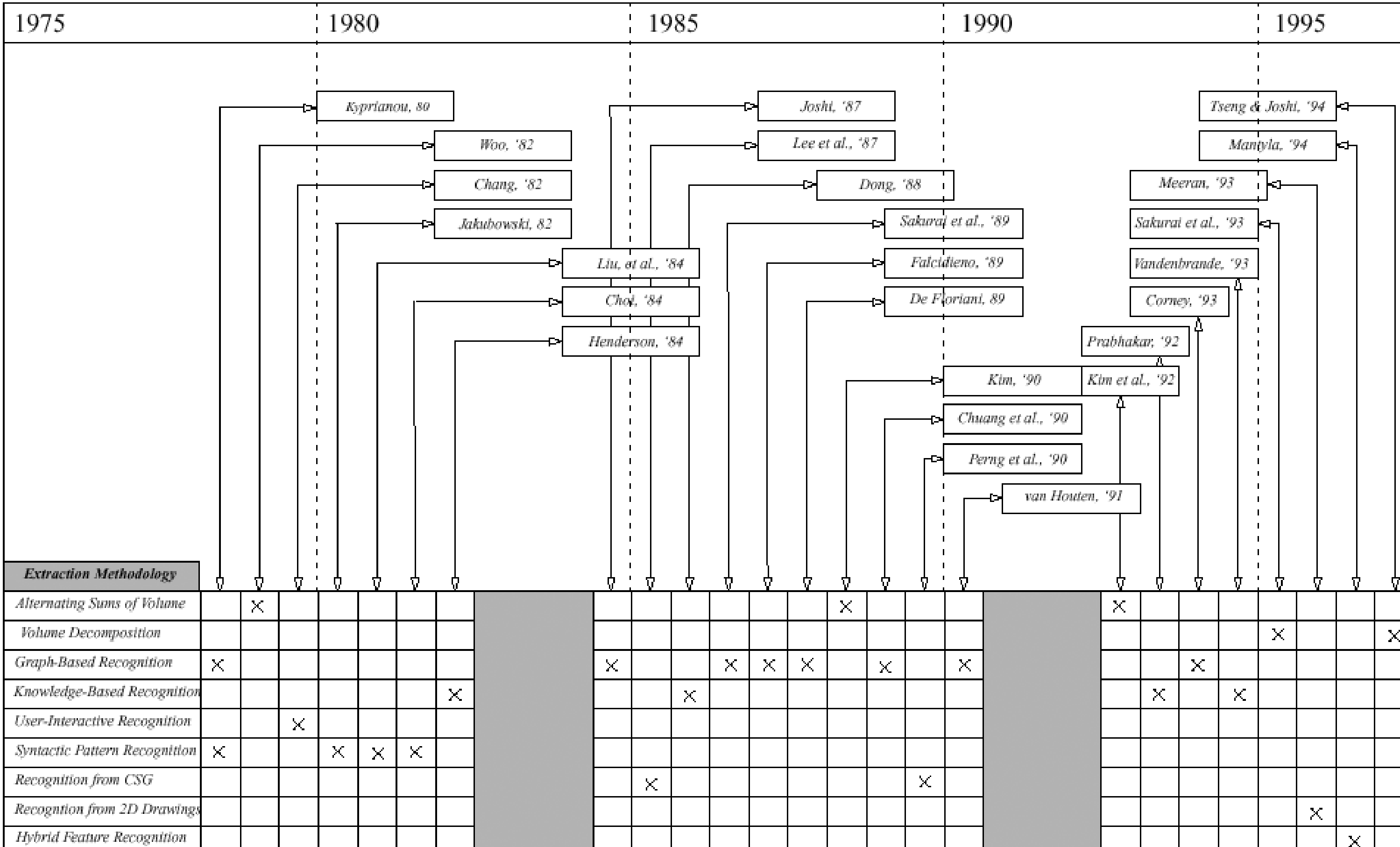

FIGURE 2.6 Chronology of feature recognition work.

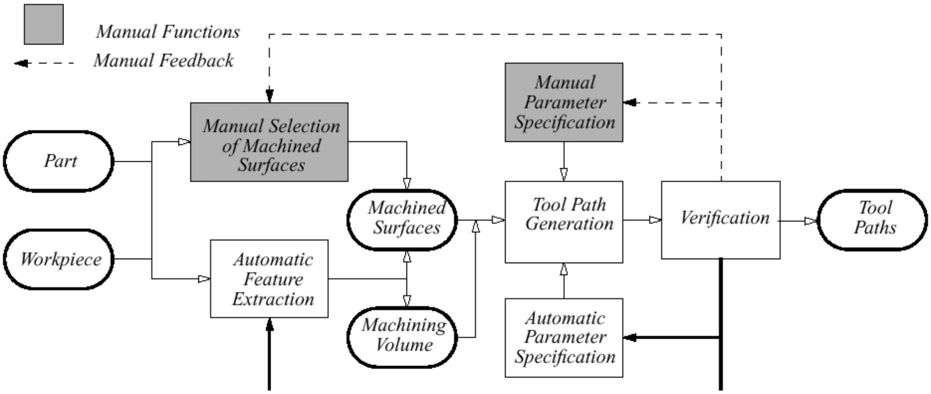

FIGURE 2.7 Volume decomposition approach to feature recognition.

2.6.2.1 Volume Decomposition

Volume decomposition approaches seek to break up the Δ *Volume** into machining volumes. This process is illustrated in Figure 2.7. One of the most well-known approaches using volume decomposition is that adopted by Sakurai and Chin (1994). In their approach, the Δ *Volume* is decomposed by extending planar and curved faces of the part into minimal cells. These cells are recombined to form maximal volumes. By subtracting these volumes in different orders, alternate volume decompositions can be generated. Tseng and Joshi (1994) have also adopted a similar decomposition process.

One advantage of the approach adopted by Sakurai and Chin (1994) is that the definition and use of maximal volumes permit their algorithm to generate all feature interpretations. They argue that this provides an opportunity "to find the optimal or near optimal feature interpretations" (Sakurai and Chin, 1994). This follows because their method is purely algorithmic as opposed to the more common heuristic approaches.

One concern about their approach is that it is driven purely by the geometry of the part. Although this enables them to create a decomposition without having to specify a feature type and domain, a priori, it raises the question as to whether or not all maximal volumes generated can be mapped to a feature within a given domain, in particular the machining domain. A second concern is whether their approach can be extended to surfaces which generate closed halfspaces, quadrics, for example.

2.6.2.2 Alternating Sums of Volume

A similar approach to volume decomposition, first proposed by Woo (1982) and known as the alternating sum of volumes (ASV), recursively subtracts the part from its convex hull until the null set is reached. Woo represented the resulting decomposition as a series of convex volumes with alternating signs. This approach was not always successful for two reasons: (1) When the convex hull at successive iterations was the same, the algorithm cycled, and (2) the algorithm did not always generate a usable decomposition from a machining perspective. A third shortcoming is similar to that of Sakuari's approach to volume decomposition: ASV is driven purely by part geometry. This is even more critical in the ASV approach, because the algorithm generates nonintersecting convex volumes, i.e., precedences are generated using only the part geometry. For machining volume decompositions, this is unacceptable since machining practices need to be considered in determining precedences. Finally, parts with curved surfaces must first be mapped to a polyhedral representation for the convex hull operator. Kim and Wilde (1992), Waco and Kim (1993), and Kim (1994) have extended the ASV approach by introducing modifications that eliminate cycling and generate machinable convex volumes.

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*The Δ *Volume* (delta volume) is a term commonly used in feature recognition to refer to the stock that must be removed from a workpiece to generate the final machined part.

2.6.2.3 Graph-Based Recognition

Graph-based feature recognition has received much attention. The basic philosophy of the approach is to represent the part model and features as graphs, and to perform feature recognition by finding subgraphs of the part graph that match feature graphs.

The first step in this approach is to represent the part as a graph. Because a boundary representation (B-rep) solid model is itself a graph, some researchers have worked directly from this representation (Sakurai and Gossard, 1990). Others have mapped the part from its original representation to other graph representations. These include Attributed Adjacency Graphs (AAG) (Joshi, 1987), Face Edge Graphs (FEG) (DeFloriani, 1989), Face Adjacency Hypergraphs (FAH) (Falcidieno and Giannini, 1989), Vertex Edge graphs (V-E) (Chuang and Henderson, 1990), and Aspect Face Edge Graphs (AFEG) (Corney, 1993). Often the arcs in these graphs are supplemented with additional geometric information. For example, Joshi (1987) tags the arcs in the AAG with 0 if the edge is concave and 1 if the edge is convex.

A decomposition step is normally performed to break up the part graph into a number of smaller subgraphs. These subgraphs may be equivalent to protrusions or depressions in the part. This decomposition step is geared to creating a more computationally manageable problem. Graph matching subsequently is performed on these subgraphs using the feature graphs as templates.

The two main problems with graph-based techniques are (1) the computational complexity of the problem as the size of the part and the number of features and their complexity increase, and (2) the problem of feature interactions which can create phantom features and mask the presence of true features.

2.6.2.4 Syntactic Pattern Recognition

Syntactic pattern recognition is closely related to graph-based techniques. In syntactic pattern recognition, a language is developed with which to represent the part model. The resulting representation is then "parsed" using a feature grammar. Features are recognized by finding combinations of literals of the language within a part representation that conform to the rules of the grammar.

One of the first applications of this approach to feature recognition was by Kyprianou (1980), who used a faceset data structure to represent the part. His algorithm first mapped the B-rep of a part to a series of facesets for depressions and protrusions of the part. These facesets are then analyzed using a feature grammar to generate a part code for the one in question. Kyprianou's work in syntactic pattern recognition is acknowledged by many as ground breaking in the field of feature recognition. It can be argued that syntactic pattern recognition is a formalization of many of the other recognition methodologies. Henderson (1984) uses such an argument in his work. Other researchers who have used this approach include Choi (1982), Jakubowski (1982), and Liu and Srinivasan (1984).

The main limitation to syntactic pattern recognition is the difficulty in developing 3D feature grammars that are general and robust enough to model features of the complexity and diversity found in design and manufacturing. Concern about the computational complexity of shape grammars also exists. Finally, customization of the recognition process requires feature grammars that must be adaptable to different applications.

2.6.2.5 Knowledge-Based Feature Recognition

One of the earliest applications of knowledge-based expert systems to the problem of feature recognition can be attributed to Henderson (1984). His approach uses feature production rules created in the logic programming language Prolog, to interrogate the part. The part itself is first converted from a B-rep into a series of Prolog facts which convey geometric and topological information about the part. The successful execution of a feature rule returns information about the feature from the part facts. This information is used to construct a feature volume which is subtracted from the Δ *Volume*. The recognition process continues until the Δ *Volume* is the null set.

Vandenbrande (1990) attempted to overcome some of the shortcomings of previous work using AI techniques. One of the primary problems he addressed was that of interacting features. He critiqued Joshi's work (Joshi, 1987) as being based on "rigid feature definitions that rely mainly on face adjacency information." When feature interactions occur, the rigidity of these definitions limits the feature-matching algorithm. This observation is the main motivation behind his work: To implement a strategy that is based on feature hints not rigid feature definitions, which can handle features incompletely represented in the object's B-rep due to feature interactions. To do this he proposed a "hint generation and testing" methodology which he implemented using an expert system shell that integrated object-oriented and rule-based programming.

Vandenbrande's approach and others based on feature hints and knowledge about feature recognition are promising. They recognize that feature recognition is a complex problem in human reasoning and approaches that handle inexact and uncertain data have a greater chance of being successful. For example, because these approaches are driven only by hints of features and not a complete representation of the feature embedded within the model, they are more robust in handling feature interactions.

2.6.2.6 User-Interactive Approaches

User-interactive recognition approaches rely on the user to select constitutive geometric elements of a feature (edges or faces) through a graphical interface. These can be viewed as hints similar to those identified automatically in other approaches (Vandenbrande, 1990). The user may be required to either select all trace elements of a feature in the model, or select a minimal set from which the other elements may be identified. Thus, a user-interactive approach need not necessarily be brute force. Rather, by minimizing the level of work that the user must do in selecting feature hints, the system can be designed to behave intelligently. User-interactive methodologies also may be coupled with automatic recognition to extend the domain of the latter.

Although some researchers have implemented user-interactive recognition, it has almost exclusively been done within the context of CAPP system development (Chang, 1982; Brooks et al., 1987; Giusti et al., 1989). The focus of these approaches has been to provide an integrated environment more than to develop an intelligent, user-interactive methodology.

2.6.3 Discussion

As is clear from the chronology in Figure 2.6, feature recognition is a problem that has been addressed by many researchers over the past 2 decades. The focus of this work has been primarily on rotational and 2.5D (prismatic) geometries. While many researchers have solved subsets of these domains, no one work provides a provably complete methodology for automatic feature extraction in either domain.

At the same time, while limitations to current solutions exist, this research highlights the inherent complexity of the problem when the objective is to develop a practical solution. A major complicating factor lies in the definition of a feature itself. Three approaches to feature definition are possible. The first is to create a standard set of features that can be used by all CAE system developers. While such a standardization is useful, deciding on a feature set broad enough to cover the requirements of all possible contexts just within the machining domain is difficult, if not impossible. The second approach attempts to address this open-endedness by proposing that features be user defined, i.e., the feature recognition methodology utilizes a feature set created by and customized to the needs of each end-user. The difficulty with this approach is that it requires representation methodologies that are generic, modular, and customizable, yet implementable in the sense that they can be integrated with the underlying recognition algorithms. The third approach is a hybrid combination of predefined feature sets and user-defined features. This approach offers the best of both worlds. It recognizes that there is a standard feature set that is applicable to many machining contexts while providing a mechanism for extending the set when the situation requires it.

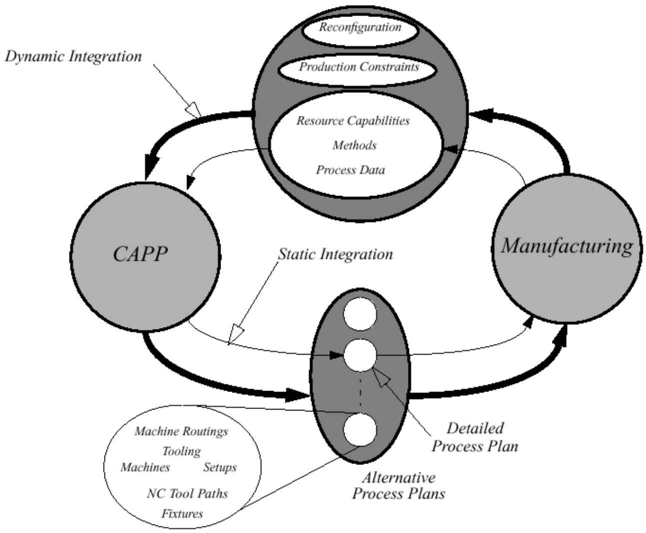

FIGURE 2.8 Integration of CAPP with manufacturing.

Recent commercialization efforts in CAPP have resulted in a number of viable feature extractors. Once such extractor comes with the PART™ CAPP system.* This system evolved from the work of Houten at the University of Twente, The Netherlands, in the mid to late 1980s (Houten, 1988; 1989a; 1989b; 1990). In PART, feature extraction is based on the hybrid notion of features. The current version of the system comes with a standard library of around 60 features to which others can be added by the user. PART also has an editing facility that allows the user to modify automatically generated results. The inclusion of this capability underscores the assertion made previously that a provably correct, fully automatic feature extraction methodology has yet to be developed.

2.7 Integrating CAPP with Manufacturing

As important as the task of integrating CAPP with automated design systems, is the task of integration with manufacturing. Figure 2.8 illustrates the relationship. CAPP provides the information to drive the manufacturing processes, yet at the same time it relies upon an understanding of the manufacturing facility (resource data, methods, process data, etc.) to constrain the planning task so that the plans created are relevant to the manufacturing context. Traditionally, this interaction has been based on a static view of manufacturing, i.e., CAPP provides a single detailed process plan for a part on a given facility that is static both in configuration and capability. This is indicated in the figure as the inner loop (thinner line). There is now, however, much interest in considering the dynamic nature of this integration by requiring CAPP systems to generate alternative process plans that conform to changing production constraints (product mix, annual volume, machine utilization) and reconfiguration of the machining facility. This is represented by the outer loop (heavier line) in the figure. Examples of research work in this area include ElMaraghy and ElMaraghy (1993), Chryssolouris et al. (1984), Lenderink and Kals (1993), and Zhang (1993).

Two components of integration that warrant special attention are NC tool path generation and machining methods. These are discussed briefly in the next sections.

*PART™ is a commercial CAPP system originally developed at the University of Twente, The Netherlands. The system was commercialized by CDC as part of the ICEM system, but has since been acquired by Technomatix Inc.

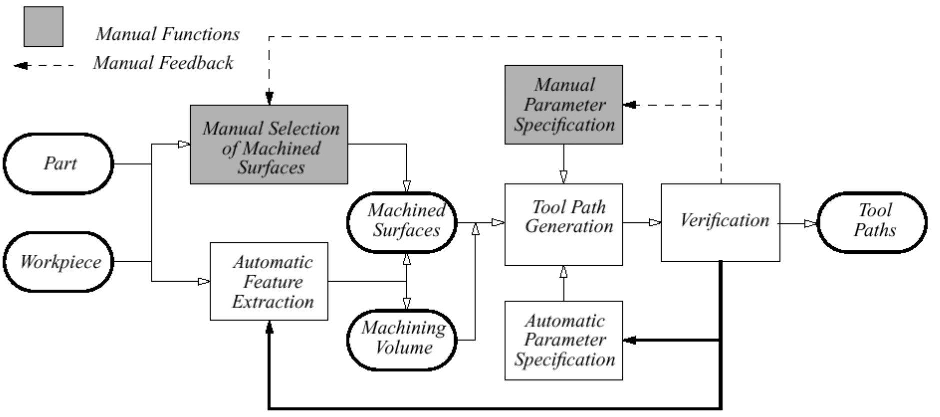

FIGURE 2.9 Role of machining feature recognition in NC tool-path generation.

2.7.1 NC Tool-Path Generation

Much work has been done on the problem of NC tool-path generation. Many commercial NC tool-path generation systems, stand alone (SmartCAM™, Gibbs™) and integrated within CADCAM systems (Bravo™, Unigraphics™, Pro-Manufacture™) are now available. While researchers are still investigating new techniques for improving tool path generation (Sarma, 1996), another major challenge that needs to be addressed is improving the ease with which these tools are used. NC part programming remains a time-intensive task.

Machining feature recognition has the potential of doing just this by driving the automation of part programming. This is illustrated in Figure 2.9. The figure also shows manual functions which give the user the ability to override any decisions made by the system as well as automatic feedback links from verification. The tasks for which automation can be helpful are

- Selection of machining surfaces
- Specification of generation parameters
- Feedback of changes from verification for the reselection of machining surfaces
- Feedback of changes based on verification for the respecification of generation parameters

As can be seen from the figure, feature extraction has the potential to eliminate the timely and error-prone task of machining surface selection because, by definition, the surfaces of the machining feature are identified. In addition, extraction procedures can be further automated to create the machining volume associated with the surface feature. This volume is useful in automating the identification and avoidance of interference geometry. Another useful output generated from feature extraction is the precedences between features. These precedences can be used to automatically merge the tool paths created for each feature into a single "tape" for machining the part.

2.7.2 Manufacturing Data and Knowledge

Machining methods (also referred to as machining practices) provide CAPP with the knowledge, expertise, and procedures that a human process planner uses. These methods may be based on sound scientific principles, experimental results, experience, or preferences established within a particular machining context. They also may be generic and applicable over a wide range of machining problems or specific to a single one.

The challenges in using machining methods within CAPP fall into the following categories:

- Identification and retrieval
- Implementation

- Maintenance
- Customization

Identification and retrieval are concerned with understanding how a human process planner applies experience and techniques to make decisions when generating process plans: What decisions are being made? What characteristics of the situation are being recognized by the planner that trigger these decisions? The main challenge here stems from the fact that human planners do not necessarily follow a consistent strategy in applying methods. The process often requires complex trade-offs of information from several sources. When one of these sources is experience, the basis of the applied method can be difficult to verify. Thus, identification and retrieval of methods are not just a bookkeeping task. Rather, it requires the cultivation of an attitude toward process planning based on a sound methodology for applying machining methods.

Methods implementation requires an approach that is general enough to capture information from very different sources while at the same time is simple enough to provide a maintainable, noncorruptible environment. Rule-based expert systems have been the most commonly adopted implementation strategy among CAPP system developers.

Because the need to update or add new methods always exists as more information becomes available or as new methods are applied to more applications, maintenance of the knowledge base becomes a key concern. As changes are made, the integrity of the information needs to be preserved. One problem occurs when new methods are added that conflict with old ones. The system needs to include a strategy for resolving such conflicts. One approach that has been used extensively with expert systems is to place the onus on a knowledgable engineer to avert such problems. However, as the size of the knowledge base grows, the cost of employing dedicated personnel for this task becomes prohibitive.

Finally, creating off-the-shelf CAPP systems with the methods included is a difficult if not impossible task. This is because it is unlikely that the system developer can capture all the desired methods from all potential users during system development. Thus, while a system may come with some generic, widely accepted methods, it must include a facility to allow new methods customized to each context to be added to the system.

2.8 CAPP for New Domains

Even though formidible problems remain in the development of commercially viable CAPP systems, researchers have continued to broaden the applicability of this technology to new domains. An example of such research is in the domain of parallel machining.

2.8.1 Parallel Machining

Parallel machining is the simultaneous removal of material from a workpiece by multiple cutting tools on a single machine tool or machining system. This concept has been in existence for some time. Examples of parallel machining are found on transfer line machines in automobile production for machining powertrain components, multi-spindle plano-milling machines for the simultaneous machining of casting surfaces and multi-turret (4-axis)* lathes. In these instances, parallel machining is preferred to sequential machining because higher production rates can be realized due to the reduction of cutting times.

The application of parallel machining in these examples suffers from one major drawback: a limitation in the range of parts which can be machined due to the dedication of the machining resources to specific tasks. Transfer lines are a prime example of this. Transfer line machines are constructed with the aim of mass producing components from a single engine model. The machining

*The term *4-axis* lathe is commonly used in industry to refer to a lathe with two turrets. Each turret is positioned by movements along an independent pair of orthogonal axes (x-axis and z-axis).

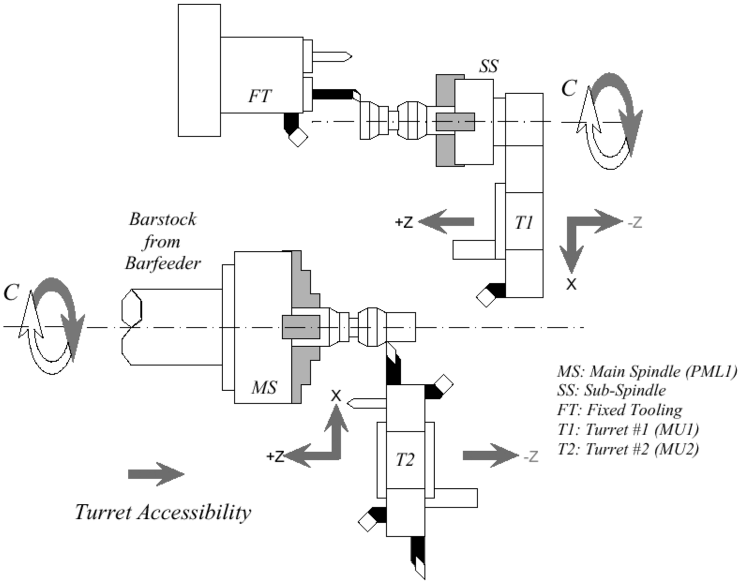

FIGURE 2.10 Examples of parallel machines.

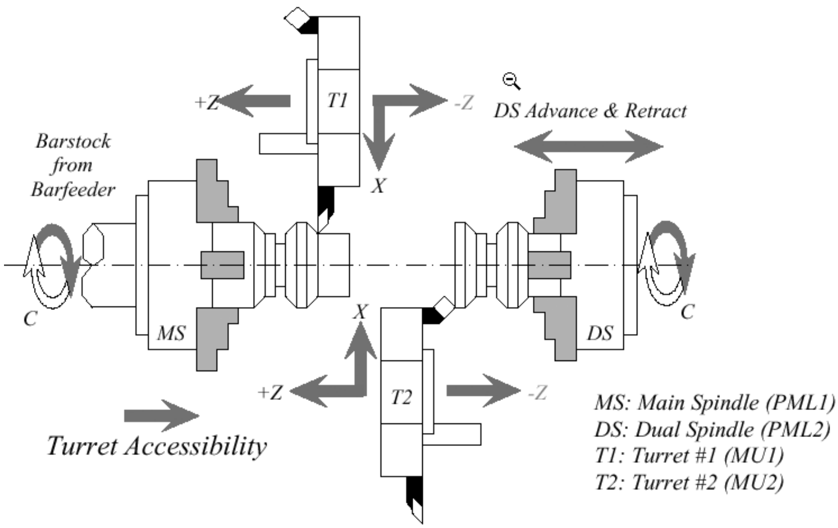

FIGURE 2.11 Example of a dual-spindle mill/turn.

elements are dedicated to this task. Once this model is taken out of production, the machines must be stripped down and retooled. This contributes to high setup costs when switching lines from an old engine model to a new one.

One class of machine tools that combines the advantages of parallel machining with the flexibility of nondedicated tooling afforded by computer numerical control (CNC) is the mill/turn (also referred to as a turning center) (Figures 2.10 and 2.11). Parallel machining on mill/turns takes two forms:

- Multiple machining operations performed simultaneously on a single part
- Multiple operations performed simultaneously on multiple parts

A secondary feature of mill/turns which adds to their flexibility is, as their name implies, the ability to perform both turning and milling operations in the same setup. This contrasts greatly with conventional machining practice which dictates that turning and milling operations be performed in separate setups on different machines. The resulting elimination of setups on mill/turns has obvious advantages in reducing the machining time per part and in increasing part accuracy by reducing work handling.

For the capabilities of mill/turns to be fully exploited, a CAPP system for the mill/turn domain must be developed. This presents problems of a different nature than those encountered for conventional CAPP systems. In particular, the presence of multiple tool- and work-holding devices raises the question of the efficient utilization of the machine tool. Considerations of the effect of parallel machining on tool wear and part quality also must be addressed. A greater need for collision checking and avoidance planning due to the simultaneous motions of multiple turrets is necessary. Currently, the complexity of process planning for this domain results in conservative process plans which underutilize the machine tool's resources.

2.8.1.1 CAPP for Parallel Machining

While a great body of work exists in the area of CAPP for the sequential machining domain, research about CAPP for the parallel machining domain is relatively new. One example of prior work in this domain is by Levin and Dutta (1992). In their work, they outline their experiences in implementing their version of a CAPP system for parallel machining (PMPS). Within PMPS, a Giffler-Thompson algorithm which generates active–delay type schedules was used to sequence machining operations. An active schedule is one in which no operation can be started any earlier without either delaying some other operation or violating a technological constraint. A delay type schedule allows a resource such as a machine tool turret to be idle instead of performing an operation. The author surmises that these two characteristics are highly applicable for process planning in this domain.

While the Giffler-Thompson algorithm is intuitively easy to understand and equally easy to implement, it is difficult to determine how good the final schedule is. In fact, because it uses a one-step look-ahead strategy, the plans are likely to be myopic in nature. Nevertheless, this work does discuss in detail the nuances of process planning for parallel machining and provides a good foundation for this research.

New approaches to scheduling for mill/turns using Genetic Algorithms have been developed by Yip-Hoi (1997). This dissertation work also makes contributions to defining an architectural framework for a CAPP system for parallel machining as well as developing numerous geometric modeling and feature extraction tools to assist the process planner in generating process plans for this domain.

2.9 Conclusions

This chapter presents a overview of research work in the area of computer-aided process planning. This field has generated much attention over the past 20 years as researchers have tried to bridge the gap between automated design and manufacturing. We have presented some of the key enablers and characteristics of CAPP systems. We also have discussed research in feature recognition, which is one of the key underlying technologies of CAPP.

Despite the efforts outlined, and extensions to new CAPP domains, fewer commercially viable CAPP systems are available than CAD or CAM systems. This is in large part due to the complexity of interpreting CAD models of complex engineered products and the difficulties in identifying and capturing machining practices that are customized to the end-user's requirements. Current trends such as the increasing use of features in CAD/CAM systems and the explosion in information engineering techniques prompted by internet development are likely to spur on a second generation of CAPP systems that will attempt to address current deficiencies.

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