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Computer-Aided Process Planning: A State of Art

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During the last decade, computer-aided process planning (CAPP) has received much attention both from researchers and practitioners. One of the reasons for this is the role of CAPP in reducing throughput time and improving quality. An attempt has been made in this paper to review the existing literature with the objective of gaining insights into the design and implementation of CAPP systems. The literature available (1989–1996) on CAPP has been reviewed based on the types of systems. The advantages and disadvantages of such systems are presented. Finally, future research directions are indicated.

Keywords: CAPP systems; Future research; Review

1. Introduction

Process planning is defined as the activity of deciding which manufacturing processes and machines should be used to perform the various operations necessary to produce a component, and the sequence that the processes should follow. Alternatively, process planning is the systematic determination of the detailed methods by which parts can be manufactured from raw material to finished product. In recent years, computer aided process planning (CAPP) has been recognised as a key element in computer integrated manufacturing (CIM). In spite of the fact that tremendous efforts have been made in developing CAPP systems, the benefits of CAPP in real-life manufacturing environments are yet to be seen. With the rapid development of computer-aided techniques, both the design and implementation of CAPP have changed greatly since its development. In the past three decades, more than 300 papers have been published in this area. Most of the papers appear to introduce only specific CAPP systems, although a few papers give a general survey (e.g. [1–6]).

With today's rapid development in science and technology, it is necessary to update information frequently so that the goals of research and development can be achieved. Over the last 30 years many CAPP systems developed were based on the variant approach, while now the generative approach and the semi-generative approach are being widely adopted. At the beginning of the 1980s, artificial intelligence (AI) techniques were introduced in CAPP. Many CAPP systems were implemented by AI techniques, usually entitled either "knowledge-based" systems or "expert" systems. Each of them has advantages and disadvantages. A lack of skilled process planners in some industrialised countries, such as in the USA [7] and UK [8], gives impetus to the development. A large number of industrial companies have acquired CAPP systems for integration of design and production and to compensate for the shortage of skilled process planners. In spite of the fact that many CAPP systems have been developed, their effectiveness is still far from satisfactory, and many large companies have had to establish their own research groups to develop their own CAPP systems. Small and medium size companies can afford only existing CAPP systems which have been developed by research organisations or universities.

A survey of the recent development of CAPP is needed to make decisions concerning CAPP implementation and to aid in guiding further research. A critical assessment of the available systems for CAPP should help to generate new ideas for future research and development. In this paper, a review of existing CAPP systems is presented.

2. Computer-Aided Process Planning (CAPP)

A detailed process plan usually contains the route, machine and tool, processes, and process parameters. A basic CAPP model is shown in Fig. 1. Since there are multiple choices for machining operations for the same machined surface, multiple machine tools available to perform the same operation, and different machining sequences, etc., alternative decisions can be made in process planning. For a machined part, there usually exist several feasible process plans for creating the part, although most existing CAPP systems are designed in such a way that only one process plan is generated. Usually, these CAPP systems work in conjunction with CAD and other computer systems. Sequential design and manufacturing follows a line path, with each step beginning after the previous step is completed.

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In short, CAPP is a decision-making process. It determines a set of instructions and machining parameters required to manufacture a part. There are four main elements in designing a CAPP system: input, output, database, and manufacturing decision-making rules [9]. As shown in the CAPP model, data preparation is a necessary step for obtaining proper product definitions for the CAPP system which is carried out after the CAD system is completed. After the completion of data preparation the data is entered into CAPP and is supported by knowledge and physical rules. When the CAPP operation is completed, the next step is output. From this output, the next operation is post processing which prepares data for production planning and scheduling activities. Finally, the production planning and scheduling operations are carried out. Those components in the dashed-line box are independent of CAD and production planning/scheduling.

There are generally two approaches to CAPP systems, namely variant and generative. The *variant* approach was used in early computer-aided process-planning systems, and is basically a computerised database retrievel approach [6]. The variant or retrieval approach is based on group technology methods of classifying and coding parts for the purpose of segregating these parts into family groups. In this approach, parts produced in a plant are grouped into part families, distinguished according to their manufacturing characteristics. For each part family, a standard process plan is established. The plan is stored in a computer file and then retrieved for new parts that belong to that family. Some form of parts classification and coding system is required to organise parts into families for correct retrieval of the appropriate plan for a new part. A major problem with this approach is the lack of adequate classification models that can provide consistency in classifying and coding parts. It is also restrictive in that new parts to be planned have to be similar to those already in the data file. The second approach to computer-aided process-planning is the *generative* type. Systems of this type synthesise the process plan for a new part, based on an analysis of part geometry, material and other factors that may influence manufacturing decisions. Inputs to the system would usually include a comprehensive description of the part. This may also involve the use of some form of part coding, but this does not involve the retrieval of existing standard plans [10]. These systems usually employ either a set of algorithms or knowledge-based techniques to progress through the various technical and logical decisions toward an appropriate process plan for a part. The generative approach provides fast advice to designers early in the design process and is closely coupled with the product-modelling activities. Once the manufacturing technology, and the type of equipment or process have been chosen, further detailed planning is carried out as usual. The use of knowledge-based systems and artificial intelligence techniques was the next major development in generative process planning [6]. A survey of reported CAPP systems from 1989 to 1996 is presented in the following section.

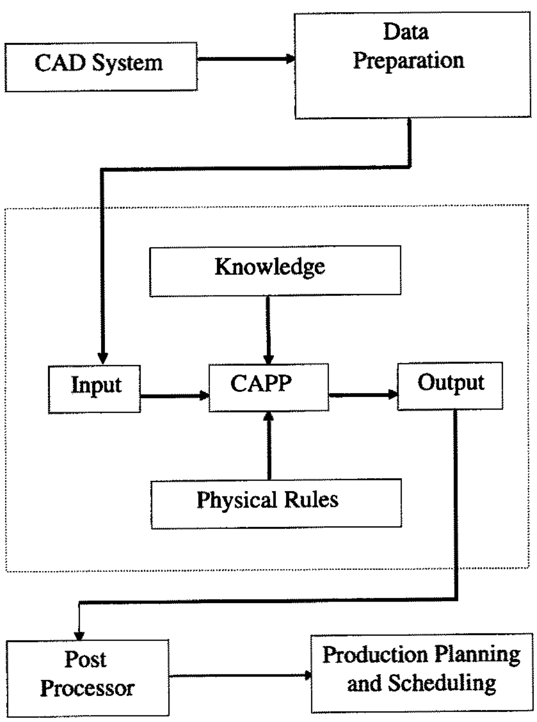

Fig. 1. Basic CAPP model.

3. A Survey of CAPP Systems

A number of surveys have been carried out in the last thirty years on the development of CAPP systems. Many keynote papers have addressed issues for the development of CAPP. Weill et al. [2] surveyed CAPP systems and addressed the technical problems in the development of CAPP, from process selection to the editing of process sheets. The survey also reported the architecture of CAPP systems for technology processing in the form of bar diagrams. More than 15 different systems were reported. The next survey work was reported three years later by Eversheim and Schulz [3] who reviewed more than 50 CAPP systems. Within the same year, another comprehensive survey was reported by Wysk et al. [11] in which more than 25 systems are reviewed. The review was further extended by Chang and Wysk [4]. Another widely used survey was carried out by Alting and Zhang [5].

In this section, some of the existing CAPP systems have been reviewed. The details of the systems developed from 1989 to 1996 are presented for their approaches, and the programming languages used. In this paper, more than 20 CAPP systems have been reviewed and are listed in Table 1. In order to show the scope of existing CAPP systems and to demonstrate the characteristics of the different systems which are implemented, a number of selected CAPP systems are discussed in the following.

3.1 COMPLAN System

COMPLAN is a generative/variant of CAPP systems [12]. This process-planning system, has been designed for small-batch manufacturing of mechanical parts and is mainly developed in the C++ language. The modules of the COMPLAN system can be arranged in two main functional groups:

process planning and workshop scheduling. The relational database is central to the system and is used to exchange and synchronise information between the modules. The COMPLAN architecture provides a framework in which all functional modules work together in a concurrent approach. The COMPLAN system follows a two-level hierarchical approach to scheduling which is performed in different time horizons, levels of aggregation to achieve better load balancing, and to obtain accurate resource assignments and rescheduling functions.

Economic competition is ever increasing, especially since the globalisation of the manufacturing business. In order to anticipate new challengers, manufacturers are urged to revise their economic objectives fundamentally. The COMPLAN system realises economic improvements such as:

1. A shortening of the lead time from design to manufacturing and reducing the effort spent to enter CAD data into a CAPP system, and by rationalising the process-planning effort needed.
2. Achieving a leaner and more flexible production organisation.

The most important feature of the COMPLAN process-planning system is its ability to handle nonlinear (manufacturing alternatives) process plans. The system provides either manual or automatic planning functions for process planning and scheduling. So, the user will at all times retain full control over the system-planning output.

3.2 ESTPAR System

ESTimator of PARameters (ESTPAR) is a generative approach to a CAPP system [13]. The knowledge-based expert system along with the GP code is called ESTPAR. The GP code was written in FORTRAN IV, and ESTPAR has been written in FORTRAN 77 for the convenience of integration with the GP code and the macro-level approach. The ESTPAR system can be used by manufacturing personnel to determine the optimal machining parameters and the corresponding machining costs when using different combinations of machines, tools, and fixtures (MTF). The ESTPAR system is also a part of a large automated process-planning system to be used by design and manufacturing engineers for efficient part design and manufacturing. The main advantage of this system is that more machining operations can be included and more functions of automated process planning can be added without any difficulty.

3.3 FCAPP/SM System

FCAPP/SM is a generative CAPP system [14]. This process planning system, which has been developed for sheet metal parts, has incorporated several features of generative systems using a procedural decision making framework. The system was developed using the Clipper language compiler. Clipper works with dBASE-compatible databases and allows the development of stand-alone systems. The part storage system consists of two main databases and several support databases. The main parts database contains one record for each part. This record stores the part name, raw material form, material, overall dimensions and tolerances, and other part-specific information. The feature database contains one record for each feature of a part. Features currently identified are holes, slots, and bends. Hence, a many-to-one relationship exists between the feature database and the parts database. The databases are linked by the part number field common to both databases. The FCAPP/SM system contains about 30 rules which match the part attributes from the part databases with the standard machine information found in a machine database. The process planning strategy adopted in this system is to arrange all the features of the part into a predetermined precedence hierarchy. Corresponding to each feature, all feasible machines are identified next. This system has the capability of adjusting to real-time problems such as machine breakdown, job priority and overloading. Unlike existing systems which use assumed weights and heuristic search strategies to obtain a feasible plan, this system uses cost data and optimisation methods to generate an optimal plan.

3.4 IKOOPP System

Intelligent knowledge-based objective-oriented process planning (IKOOPP) is a generative CAPP system [15]. Because of the problems associated with manual process planning, and the inconsistencies of the plans, the IKOOPP system has been developed to automate and standardise the process planning function for the manufacture of progressive dies. The IKOOPP system receives part definition data from a commercially available die design system called Auto-Trol Series 7000 Die Design. A feature extractor has been developed to extract the relevant attributes of machining features within a progressive die plate mode. These attributes are used by the IKOOPP system to reconstruct the plate model using an object-oriented representation for the subsequent reasoning processes. Knowledge of the functions of the machining features are used to deduce engineering information which cannot be represented easily in the CAD system. Moreover, the available interface for accessing the Auto-Trol databases is limited to a set of FORTRAN subroutines. The IKOOPP system automatically plans the set-up sequences, and selects the required machine tools, cutting tools, heat treatment, fixturing elements and sequence of operations.

3.5 KAPLAN System

Knowledge-based approach to process planing (KAPLAN) is a generative CAPP system [16]. KAPLAN provides fully automatic generation of productions plans of rotational parts. The program structure is based on knowledge base techniques and the knowledge required for the plan generation is represented by IF-THEN rules, easily adapted to every workshop environment by means of a user interface. The application of this technique is particularly effective where flexible plants and machine tool are used for a widely variable group of products, e.g. in flexible manufacturing systems. The module for the automatic generation of turning sequences, (KAPLAN) is a part of a more complex process-planning system for the programming and the control of a flexible cell. A great advantage

Table 1. Details of the CAPP systems (1989–1996).

System	Approach	Programming language	References
AFR	Generative		Jung and Lee [22]
ALPS	Generative	Clipper language compilar with dBASE	Catron and Ray [23]
AMOPPS	Generative	Turbo Pascal	Yeh and Fischer [24]
CADEXCAP	Generative and variant	Fortran 77 and POP 11	Katta and Davies [25]
CAMSS	Variant		Gim et al. [26]
COMPLAN	Generative and variant	C++	Schweiz [12]
CROPS	Generative	OPSS	Guoit et al. [27]
ESTPAR	Generative	Fortran 77	Narang and Fischer [13]
FBD	Generative		Jung and Lee [22]
FCAPP/SM	Generative	Clipper language compilar with dBASE	Smith et al. [14]
GEOPDE	Generative	Prolog	Hsu and Lee [28]
GFAS	Generative	ECSL	Hutchinson [29]
GLM	Variant		Myer et al. [30]
IKOOPP	Generative	Fortran Auto-Trol series 7000	Lee et al. [15]
KAPLAN	Generative	IF-THEN rules	Giusti et al. [16]
K-base	Generative	Turbo Pascal	Luong and Spedding [17]
MCOES	Generative	LISP	Opas et al. [18]
PART	Generative		Boogert et al. [31]
PerMIA	Variant		Elsayed and Chen [32]
RDCAPP	Generative and variant	FORTRAN SQL	Athar Masood and Srihari [33]
ROBEX and RATE	Generative	OPSS	Browne et al. [19]
SMT	Generative and variant	LISP	Srihari and Raghavan [34]
TAB	Generative and variant	LISP	Srihari and Raghavan [34]
TAMCAM	Semi generative	dBASE	Lee et al. [15]
TVCAPP	Generative	Turbo Pascal	Abdous and Cheng [21]

in terms of time and data reliability is obtained by this CAD-CAPP integration. The technique for generating plans used by this system is quite different from those used by the other systems currently proposed and represents a new approach in CAPP systems for rotational parts.

3.6 K-Base System

A knowledge-based (K-B) system is a generative CAPP system [17]. Initially this system was written in Prolog, but when it was redesigned for more generic applications, it was re-coded in Pascal, and runs on IBM compatible computers. A knowledge-based system is used for process planning and cost estimation in the hole-making process. The main function of the system, besides estimating the cost of production, is to recommend appropriate processes, their sequence and their respective machining conditions in order to obtain the required product specifications. The knowledge required for process planning and cost estimation is organised into three knowledge bases, namely process and sequence knowledge base, machinability data knowledge base and costing data knowledge base. In comparison with the manual system previously used, this system has provided several advantages including the flexibility to change data, and uniform process plans, correct machining parameters, and automatic cost estimation. Another important feature of the system is that it provides a company with a facility to store the knowledge gained by experienced planners in the databases which can then be used to assist inexperienced planners to perform the task of planning and estimating quickly and efficiently. A major feature of this system is that it unifies process sequence, machinability, and cost estimation into an integrated system which caters for the requirements of small to medium sized companies involved in batch operations.

3.7 MCOES System

Manufacturing cell operator's expert system (MCOES) is a generative CAPP system [18]. The architecture of the MCOES system consist of five main subsystems:

1. A design data interface.
2. A process plan preparation system (strategic process planning).
3. A process plan generation system (operative process planning).
4. A method editing interface.
5. A factory modeller.

The overall operation of the system takes place in three stages:

1. *System set-up stage.* When a factory model representing factory facilities is generated and a collection of methods representing tested, proven manufacturing processes is created. In this stage, the planning focus is on a single process.
2. *Strategic process planning stage.* When a process plan specification for a new product family is created by choosing appropriate methods and set-ups. In this stage, the planning focus is a single product family, comprising several processes.
3. *Operative process planning stage.* When a detailed process plan is created for a given manufacturing order. In this

stage, the focus is on a single order, possibly comprising several instances of several product families.

The main advantage of this system is that it is easy to generate correct part programs on the basis of relatively high-level-order information, in a few minutes.

3.8 ROBEX and RATE

RObot Based EXpert (ROBEX) system, and robotic assembly time estimators (RATE) are generative CAPP systems [19]. Robot-based flexible assembly systems are complex and their planning and development requires a methodological planning procedure. The two systems are designed as a part of an overall planning procedure for the design of robot-based flexible assembly systems. This seven-step planning procedure provides an integrated approach to robot integration in CIM systems, from the initial feasibility studies to the final detailing of the flexible assembly system design. ROBEX and RATE belong to the second step, the determination of basic data. The purpose of this step is to determine the information which will be needed in the subsequent layout and planning of the assembly systems, i.e. a feasible set of assembly operations by which the product can be assembled, and estimated assembly times can be determined for this set of operations. Highly accurate assembly times are not necessary at this step in the planning procedure. What is required, and what RATE provides, are estimates of the operation times, which can be used in the subsequent simulation and evaluation of the proposed assembly system. The lead time between design and manufacture of production can easily be reduced when using these systems.

3.9 TAMCAM System

TAMCAM is an open manufacturing system, developed by Smith et al. [20]. A three-level hierarchical control architecture is employed in TAMCAM. Based on the functional characterisation of shop floor control functions, a set of procedures for testing the intelligent control of a manufacturing system has been set up [20]. In TAMCAM, part design and process planning is integrated in the AutoCAD (Autodesk, Inc.) environment on a Unix platform. Each machinable feature of a part is drawn in a dedicated AutoCAD layer. The process planning system used in TAMCAM adopts a semi-generative approach, i.e. the standard process plans for a set of part families are stored in a database, and changes in a part design are resolved using decision-tree logic. The standard process plan for a part includes operations, resources, machining parameters, machine independent cutter location data (CLDATA) for each feature, and machining precedence of the features. The process-planning system can generate new process plans (including CLDATA) for a feature when the feature is changed in terms of location, shape, and tolerance. The advantage of this system is that a number of open system standards for CIM have been developed to reduce the costs associated with software development, integration, and maintenance.

3.10 TVCAPP System

Tolerance verification in computer aided process planning (TVCAPP) is a generative CAPP system [21]. The TVCAPP is an expert system, and it has 3 components.:

1. Databases.
2. Qualifiers and variables.
3. Algorithms and external programs.

TVCAPP integrates the combined effects of process selection, machine selection, tool selection, machining parameters and tolerance requirements in developing more efficient alternative process plans. The main advantages of the TVCAPP system over existing ones are that it:

1. Verifies the input values of tolerance by the user or from an AUTOCAD drawing.
2. Checks tolerance values against standards (CSA-B78.2-86).
3. Generates four types of geometric tolerances: straightness, circularity, cylindricity and concentricity.
4. Generates a limited number of operations for the statistical process control analysis.
5. Generates alternative process plans in which each operation has an operation index.
6. Calculates the cost for each process.

The proposed expert system should lead to the development of a systematic means for automatic CAD/CAPP integration from a given CAD drawing, machine and tool databases.

4. Comments on the CAPP Systems

In the previous section, some of the existing CAPP systems have been reviewed. The details of the systems available during the survey period are mentioned in Table 1. Statistics of general features for these existing CAPP systems are listed in Table 2. Plannable workpiece statistical results are presented in Table 3. Finally, Table 4 shows the statistics of implementation environments of the surveyed CAPP systems.

Table 2 indicates the approaches adopted in the development of CAPP systems. Here the use of the generative approach is higher, i.e. 64%, compared to the other approaches used in the 25 CAPP systems surveyed. The researchers preferred this type of approach because its main function is to synthesise a new plan for each specific part. The major advantage of this approach is that the process plan is consistent and fully automated. The remaining approaches are based on group technology concepts but their disadvantage is that the quality of the process plan still depends on the knowledge background of a process planner. As a research field to enable the necessary integration within the CIM concept, the generative approach is important and so most of the researchers adopted the generative approach in the development of new CAPP systems.

Table 3 indicates the statistics of plannable workpieces for the CAPP systems. Twenty percent are mechanical assembly type systems. The reason for developing this type of system is that, since the cost minimisation is the criterion for optimis-

Table 2. Statistics of general features.

General features	Quantity	Percentage (%)
Generative approach	16	64
Variant approach	3	12
Semi generative approach	1	4
Generative and variant approach	5	20

Table 3. Statistics of plannable workpieces.

Plannable workpieces	Quantity	Percentage (%)
Only rotational	3	12
Only prismatic	1	4
Only sheet metal	3	12
Only holes	2	8
Both rotational and prismatic	2	8
All (rotational, prismatic, sheet metal)	2	8
Mechanical assembly	5	20
Electronic assembly	2	8
Unknown	5	20

ation, the number of different machines and handling delays are automatically minimised in the operation sequence. The limitations of other systems are that most of them are mainframe based, and they are expensive and too complicated for shopfloor use. As a result, they require high initial capital which is often beyond the reach of small to medium-sized companies. Mechanical assembly type systems are part of larger automated process-planning systems for use by design and manufacturing engineers for efficient part design and manufacturing.

Finally, Table 4 indicates the languages used during the development of new CAPP systems. The percentage using FORTRAN is higher, i.e. 16%, when compared to other languages. This language has convenient features for performing algebraic calculations and is more applicable to scientific, mathematical, and statistical problems than other languages.

Present CAPP systems only offer partial solutions. They are limited in scope and are isolated from the rest of the manufacturing functions. They offer poor or no interface to functions such as order management, engineering and design, capacity planning, scheduling, tool management, material management, quality control and purchasing as well as existing databases [6]. As CAPP is a wide area and so many technologies have been involved in the research and implementation of CAPP systems, as well as the rapid development of today's computer-aided techniques, it is not easy to predict future trends. However, it is necessary now to review the techniques used in existing systems and to anticipate future development. In order to present the comments, some of the CAPP systems are selected.

Table 4. Statistics of implementation environments.

Implementation environment	Quantity	Percentage (%)
Turbo Pascal	3	12
Fortran family	4	16
OPSS	2	8
C++	1	4
Clipper language compilar with dBASE	3	12
Prolog	1	4
ECSL	1	4
IF-THEN rules	1	4
LISP	3	12
Unknown	6	24

The ESTPAR system incorporates a knowledge-based expert system for determining optimal machining parameters for each pass required on the surface of the part. The main advantage of this system is that the methodology has been developed such that more machining operations can be included and more functions of automated process planning can be added without much difficulty. However, considerable research work in different aspects of manufacturing is needed before the results can be used without any human intervention. The methodology has been developed for turning operations only. The equations and constraints for other machining operations need to be developed, if necessary, by machinability studies. Work needs to be done in relating tolerance and surface finish specifications to feedrate and other parameters based on different machine tools, cutting tools, and workpiece material combinations. The stable cutting regions for common workpiece materials and tools need to be determined to make optimal use of the available resources.

The FCAPP/SM system represents a practical approach to process planning. The use of features and feature-precedence graphs unifies group technology classification and coding and feature-based generative CAPP concepts. This representation, unlike the GT part family code number technique, allows flexibility in data storage/retrieval as well as in process plan generation. This approach also allows company-specific process planning rules to be identified from the feature graph instead of relying on a generic rule base. Future process planning research should concentrate on seeking such pre-existing feature precedence hierarchies instead of adopting variant/GT part family or rule-based expert-system strategies.

The IKOOPP system has been developed to automate and standardise the process planning function for the manufacture of progressive dies. However, the machining allowances are defaulted for both the roughing and semi-finishing operation. The main deficiency with feature-based modelling is associated with the difficulty in representing composite features with complex curves and sculptured surfaces. A proposed methodology for overcoming this deficiency is to have a user interactively identifying complex features from basic geometrical features and entities. Nevertheless, it is argued that feature-based product modellers with the capabilities to represent technological information will facilitate the reasoning process and thereby support the development of a fully automated CAPP system.

The SMT-TAB CAPP system, in its current state, considers single-sided PCBs with SMT and TAB components. This system could be expanded to accept and plan for all types of PCBs (SMT and through-hole technology with TAB), with boards populated on both sides. Other possible enhancements include consideration of one-layer and two-layer tape preparation, bumped tape and area TAB, and other types of encapsulation for TAB packages. The SMT-TAB CAPP system developed does not evaluate and estimate the cost associated with the manufacture of a specific PCB. This prototype system can be enhanced further to consider the shop floor status of the machines, making it a truly real-time, and dynamic CAPP system.

The expert system, TVCAPP, starts by extracting and verifying dimensional and geometrical tolerances for each machining surface. For future research, although the proposed expert system has shown many improvements over existing ones and has expanded the horizon in dealing with the tolerance verification problem, further studies need to be investigated, particularly with respect to the development of an interface program to integrate CAD and CAPP through a more general neutral file, such as IGES, and expanding the number of rules and the size of the database.

5. Suggestions for Future Research

The following are some of the future research directions for CAPP systems:

1. Architecture and constraints for machining operations should be considered while developing a CAPP system. In this connection, tolerance and surface finish specifications related to feedrate and other parameters for different machine tools, cutting tools, and workpiece material combinations require more attention.
2. Process-planning research should focus on pre-existing feature precedence hierarchies instead of adopting variant/group technology part family or rule-based expert system strategies.
3. The feature-based modelling deficiency should be overcome so that a user can interactively identify complex features from basic geometrical features and entities.
4. A CAPP prototype system has to be enhanced to consider the shop floor status of the machines, making it a truly real-time, and dynamic CAPP system.
5. An interface program should be developed to integrate CAD and CAPP through a more general neutral file, such as IGES (initial graphics exchange specification) by expanding the number of rules and the size of the database.
6. A major limitation with existing systems is that most of them require mainframe computers which are too expensive and complicated for shop floor use. As a result, they require high initial capital outlay and a long learning curve which are often beyond the reach of small and medium-sized companies. There is also a notable absence of the cost estimating capability in most of the existing CAPP systems. Therefore, a CAPP system has to be developed to offer an integrated facility for process planning and cost estimation to cater for small and medium-sized companies, which account for a large part of the machining activities in the metals industry.
7. The existing expert systems lack adequate mathematical calculation functions. Therefore, new mathematical models have to be developed to minimise the manufacturing time and cost.
8. A knowledge-based system for CAPP should be developed for integrated and intelligent process planning systems.
9. The stable cutting region for common workpiece materials and tools needs to be determined to make optimal use of the available resources. Options, such as the ability to use different machine tools for roughing and finishing passes, need to be included in an integrated package for effective use of manufacturing capabilities.
10. Most of the CAPP systems are unable to cope with the uncertain nature of the shop floor. These systems are static in nature because they deal with complete, certain and well-defined information. The implementation of a CAPP system in a manufacturing environment requires the capability of handling problems such as machine breakdown, tool failure, and alternative route generation on a real-time basis. Therefore, a CAPP system that serves as an integral CIM component and considers the dynamic and uncertain nature of the shop floor needs to be developed.
11. Intelligent CAPP systems will play an important role in modern manufacturing industry but only a limited number of intelligent CAPP systems are available. Therefore, further research is required on these systems.

6. Conclusions

The importance of CAPP in a modern manufacturing facility cannot be underestimated. CAPP provides a direct link between design and manufacturing. It reduces the time spent between part design and actual manufacture. The CAPP systems of the future should be dynamic, flexible and intelligent. The successors to intelligent systems will be "learning systems" that can monitor production and feed data back to the system. This feedback will become the teacher. The systems will be able to learn from manufacturing mistakes and therefore improve the performance. The advantages of a learning and self-adapting system should include more accurate time and cost estimates, improve productivity, ability to monitor processes, less variability, more reliability and reduced human involvement. The CAPP area has been greatly developed in the last two decades and many techniques have been involved. An attempt has been made to present the state-of-the-art of CAPP systems developed during the period 1989–1996. Some of the well-known CAPP systems are discussed in this paper. The discussion focuses on the general aspects of the systems, such as, functions, working steps, approaches of implementation, methodologies of knowledge representation, programming language, architecture, and pros and cons of the system.

References

1. H. J. Steudel, "Computer-aided process planning: past, present and future", *International Journal of Production Research*, **22**(2), pp. 253–266, 1984.
2. R. Weill, G. Spur and W. Eversheim, "Survey of computer aided process planning systems", *Annals CIRP*, **31**(2), pp. 539–552, 1982.

3. W. Eversheim and J. Schulz. "CIRP technical reports: survey of computer aided process planning systems", *Annals CIRP*, **34**(2), pp. 607–614, 1985.
4. T.-C. Chang and R. A. Wysk, *An Introduction to Automated Process Planning Systems*, Prentice-Hall, Englewood Cliffs, New Jersey, 1985.
5. L. Alting and H. C. Zhang, "Computer aided process planning: the state-of-the-art survey", *International Journal of Production Research*, **27**(4), pp. 553–585, 1989.
6. H. A. Elmaraghy, 1993, "Evolution and future perspectives of CAPP", *Annals CIRP*, **42**(2), pp. 739–751, 1993.
7. C. Emerson and I. Ham, "An automated coding and process planning system using a DEC PDP-10", *Computer and Industrial Engineering*, **6**(2), pp. 159–168, 1982.
8. B. J. Davies, I. L. Darbyshire, A. J. Wright and M. W. Park, "The integration of process planning with CAD CAM including the use of expert systems", *Proceedings of the International Conference on CAPE*, Edinburgh, UK, pp. 35–40, April, 1986.
9. M. R. Henderson and G. J. Chang, "FRAPP: automated feature recognition and process planning from solid model data", *Proceedings International Conference on Computers in Engineering*, vol. 1, ASME, pp. 529–536, 1988.
10. L. H. S. Luong, "Process planning via computer assisted classification and coding", *International Journal of Advanced Manufacturing Technology*, **4**(3), pp. 311–320, 1989.
11. R. A. Wysk, T. C. Chang and I. Ham, "Automated process planning systems: an overview of ten years of activities", *1st CIRP Working Seminar*, Paris, 22–23 January 1985.
12. S. Schweiz, 1995, "Esprit project 6805 COMPLAN. Final deliverable – detailed design document", *Internal Report of the COMPLAN Group*, June 1995.
13. R. V. Narang and G. W. Fischer, "Development of a frame work to automate process planning functions and to determine machining parameters", *International Journal of Production Research*, **31**(8), pp. 1921–1942, 1993.
14. J. S. Smith, P. H. Cohen, J. W. Davis and S. A. Irani, "Process plan generation for sheet metal parts using an integrated feature-based expert system approach", *International Journal of Production Research*, **30**(5), pp. 1175–1190, 1992.
15. I. B. H. Lee, B. S. Lim and A. Y. C. Nee, 1993, "Knowledge-based process planning system for the manufacture of progressive dies", *International Journal of Production Research*, **31**(2), pp. 251–278, 1993.
16. F. Giusti, M. Santochi and G. Dinii, "KAPLAN: a knowledge-based approach to process planning of rotational parts", *Annals CIRP*, **38**(1), pp. 481–484, 1989.
17. L. H. S. Luong and T. Spedding, "An integrated system for process planning and cost estimation in hole making", *International Journal of Advanced Manufacturing Technology*, **10**(6), pp. 411–415, 1995.
18. J. Opas, F. Kanerva and M. Mantyla, "Automatic process plan generation in an operative process planning system", *International Journal of Production Research*, **32**(6), pp. 1347–1363, 1994.
19. J. Browne, K. Terney and M. Walsh, "A two-stage assembly process planning tool for robot-based flexible assembly system", *International Journal of Production Research*, **29**(2), pp. 247–266, 1991.
20. J. S. Smith, R. A. Wysk and S. B. Joshi, "A formal functional characterization of shop floor control", *Texas A&M University working paper*, 1993.
21. G. Abdous and R. Cheng, "TVCAPP, tolerance verification in computer-aided process planning", *International Journal of Production Research*, **31**(2), pp. 393–411, 1993.
22. M. Y. Jung and K. H. Lee, "ACAD/CAPP interface for complex rotationally symmetric parts", *International Journal of Production Research*, **34**(1), pp. 227–251, 1996.
23. R. A. Catron and S. R. Ray, "ALPS: a language for process specification", *International Journal of Computer Integrated Manufacturing*, **4**, pp. 105–113, 1991.
24. C.-H. Yeh and G. W. Fischer, "A structured approach to the automatic planning of machining operations for rotational parts based on computer integration of standard design and process data", *International Journal of Advanced Manufacturing Technology*, **6**(3), pp. 285–298, 1991.
25. M. Katta and B. J. Davies, "CADEXCAP: integration of 2D CAD models of turned components with CAPP", *International Journal of Advanced Manufacturing Technology*, **8**(3), pp. 145–149, 1993.
26. J.-S. Gim, D. W. Cho and K. S. Taraman, "Optimization of face-milling cutters by use of a computer aided milling system simulator", *International Journal of Advanced Manufacturing Technology*, **6**(3), pp. 263–284, 1991.
27. T. Guiot, P. Lecocq, P. Vandereyken and M. Dumont, "CROPS: Implementation of a knowledge-based system to plan and monitor the production of a flexible line", *International Journal of Advanced Manufacturing Technology*, **4**(3), pp. 269–280, 1989.
28. Q. C. Hsu and R. S. Lee, "Geometry-oriented knowledge-based system for preliminary process design of cold-forged parts", *International Journal of Advanced Manufacturing Technology*, **6**(1), pp. 45–61, 1991.
29. G. Hutchinson, "Technology constrained process planning", *Proceedings of NSF Design and Manufacturing Systems Conference*, Austin TX, pp. 1051–1058, 1991.
30. R. H. Myer, A. I. Khuri and G. Vining, "Response surface alternatives to the Taguchi robust parameters design approach", *The American Statistician*, **46**(2), pp. 131–139, 1992.
31. R. M. Boogert, H. J. J. Kals and F. J. A. M. Van, "Tool paths and cutting technology in computer aided process planning", *International Journal of Advanced Manufacturing Technology*, **11**(3), pp. 186–197, 1996.
32. E. A. Elsayed and A. Chen, 1993, "Optimal levels of process parameters for products with multiple characteristics", *International Journal of Production Research*, **31**(5), pp. 1117–1132, 1993.
33. Athar Masood and K. Srihari, 1993, "RDCAPP: a real time dynamic CAPP system for an FMS", *International Journal of Advanced Manufacturing Technology*, **8**(6), pp. 358–370, 1993.
34. K. Srihari and Q. Raghavan, "SMT-TAB: A process planning system for PBC assembly using TAB and SMT", *International Journal of Advanced Manufacturing Technology*, **9**(5), pp. 311–323, 1994.