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A State-of-the-Art Survey on Product Design and Process Planning Integration Mechanisms

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Abstract

Integration of design systems and process planning systems is vital to the competitiveness of manufacturers and their ability to respond rapidly to market changes. In response to industrial needs, this report provides a state-of-the-art survey in technologies for the integration of product design and process planning. The survey includes high level industrial needs, available system integration architectures, process models, data models, data base systems, and interface specifications. From the survey, this report highlights key problems and recommends an approach toward design and process planning integration.

Keywords: computer-integrated manufacturing, computer-aided design, computer-aided process planning, architectures, information models, interfaces

Introduction

Process planning is the activity which links design and manufacturing. As such, the integration of computer-aided design (CAD) and computer-aided process planning (CAPP) systems is a critical element of rapid response manufacturing. Among manufacturers, various levels of integration between these activities exist [4]. At the lowest level of the state-of-the-practice, there is no integration of these systems. Design information exists on paper in the form of engineering drawings and specifications. These drawings, which may be produced as prints from master drawings or as pen plots from a CAD system, are passed “over the wall” to manufacturing engineers who produce process plans, tool paths, and numerical code (NC) programs. This practice is time consuming, error prone, labor intensive and, therefore, expensive. It often results in the redesign and re-engineering of products.

With minimally integrated design and process planning systems, graphical design information exists as digital data generated by a CAD system. Design data is sent directly or indirectly to Manufacturing Engineering for input to CAPP and NC code generating systems. This data usually exists in a standard format and is exchanged as a neutral file or through a translator. With the direct approach, information is exchanged unidirectionally from a CAD system to a CAPP system. With the indirect approach, information is exchanged unidirectionally from a CAD system to a common data base and finally to a CAPP system. Although an improvement over the no-integration scenario, problems still exist at this level. This scenario does not support a concurrent engineering approach as the systems are not interoperable. Design and manufacturing engineering activities are accomplished independently of each while the computer-based applications act as “islands of automation.” Moreover, these applications, which may come from different vendors and run on various hardware and software platforms, often do not support or facilitate the transfer of information among each other. The incompatibility of data representations and the limited connectivity between these systems further compounds their isolation. With the direct approach in particular, data integrity cannot be assured. Users often must store pieces of product life cycle data in different formats and in different data repositories which may result in redundant and inconsistent data. The general state-of-the-practice can be characterized as moving from the direct approach to the indirect approach.

A higher level of integration should resolve many of the problems associated with the state-of-the-practice. This higher level should consider the relationship between design and process planning activities in support of concurrent engineering principles. In addition to the exchange of engineering information, this level of integration must provide CAD and CAPP systems with mechanisms for requesting information and services from each other. The mechanisms may include, among others, predefined data models, interface protocols and message formats. For example, an optimal design decision may require some manufacturing information. To satisfy this requirement, a design system needs to interoperate with a process planning system by requesting information or services from the CAPP system. Several exchange models have been developed to support this level of integration.

Significant opportunities and challenges exist for realizing higher levels of integration among manufacturing systems. While those levels of integration are loosely defined, work is underway to define them. Characteristics for measuring the level of integration among systems have been identified. The characteristics to be measured include:

- The sophistication of mechanisms used to provide connectivity between manufacturing systems such as CAD and CAPP systems (e.g., data transfer over a network using standard protocols).
- The degree of coupling between systems in terms of the amount of information shared between these systems in real time.

- The level of interoperability which supports replacements of systems by “plug-compatible” implementations.
- The use of established products and standards.
- The level of overall quality between the integrated systems regarding performance, capacity, reliability, and maintainability.

Members of the National Center for Manufacturing Science’s (NCMS) Rapid Response Manufacturing (RRM) consortium[1] have identified integration among computer-based manufacturing applications as a topic which requires further investigation. The need to study the integration of design and process planning resulted in a workshop held at NIST [37] at which this integration issue was specifically addressed and culminated in this survey paper. This survey examines the state-of-the-art regarding mechanisms for integrating product design and process planning and differs from other surveys which focus on the state-of-the-art of either design [10], [11], [33] or process planning [1], [6], [39]. Moreover, this survey intends to stimulate work on this topic in the context of rapid response manufacturing. The scope of this survey includes design and process planning for discrete parts production. A broad interpretation of process planning is used: process planning for production, assembly, and inspection all fall within scope. The sources of information for this survey include manufacturers, standards development organizations, and research institutes.

This report describes existing architectures for CAD and CAPP systems integration, relevant information models (including data and activity models), and interfaces. This framework of architectures, information models, and interfaces is based upon the National Institute of Standards and Technology’s (NIST) Manufacturing Systems Integration (MSI) project [29]. Moreover, this survey identifies technology voids and obstacles to integration. Lastly, this paper recommends an approach for advancing design and process planning integration.

1. The NCMS RRM consortium is funded in part by an award from the National Institute of Standards and Technology’s Advanced Technology Program.

Integration Architectures

This section examines architectures for integrating design and process planning systems, through examples of integrated design-to-process planning systems described in the literature. An architecture defines the components of a system and the relationships among those components. Five architectures are examined: the Rapid Acquisition of Manufactured Parts (RAMP) Product Data Translation System for Mechanical Parts (RPTS MP) coupled with the Generative Process Planning Environment (GPPE), the Quick Turnaround Cell (QTC), the Design-for-Assembly/Computer-Aided Assembly Process Planning (DFA/CAAPP) system, the Knowledge-based Computer-aided Process Planning System (KCAPPS), and XTURN. RPTS/GPPE, QTC, DFA/CAAPP, and KCAPPS have architectures which consider design and process planning as primarily sequential activities. XTURN describes an architecture which considers design and process planning as concurrent activities.

RPTS MP and GPPE

The RAMP program of the South Carolina Research Authority (SCRA) currently addresses design and process planning integration with two separate systems: RPTS MP [41] and GPPE [40]. RPTS MP enables the translation of technical data into a standard digital format. As illustrated in Figure 1, a user models a part with a design tool based on parametric, feature-based solid modeling technology. The design uses non-native features which conform to the form feature specification of Standard for the Exchange of Product Model Data (STEP) [22]. The source of the model may be a paper drawing, an aperture card, or a digital file in a format which the design tool supports as input (e.g., IGES). Once a part model exists within the design tool, RPTS MP captures the part data and creates an output file for downstream applications such as process planning. In addition to form feature data, this file contains the following data in STEP format: basic part shape; datum planes and datum axes; dimensions and tolerances; geometric dimensions; surface finish; and notes and specifications.

Downstream, GPPE fuses data from various sources to generate a macro process plan consisting of high level shop floor routing which includes fabrication times and a bill of material. GPPE attempts to make intelligent planning recommendations based primarily on the knowledge of manufacturing engineers. As shown in Figure 2, additional sources of information include STEP data produced by RPTS MP and resource data describing materials, workstations, tools, and time standards.

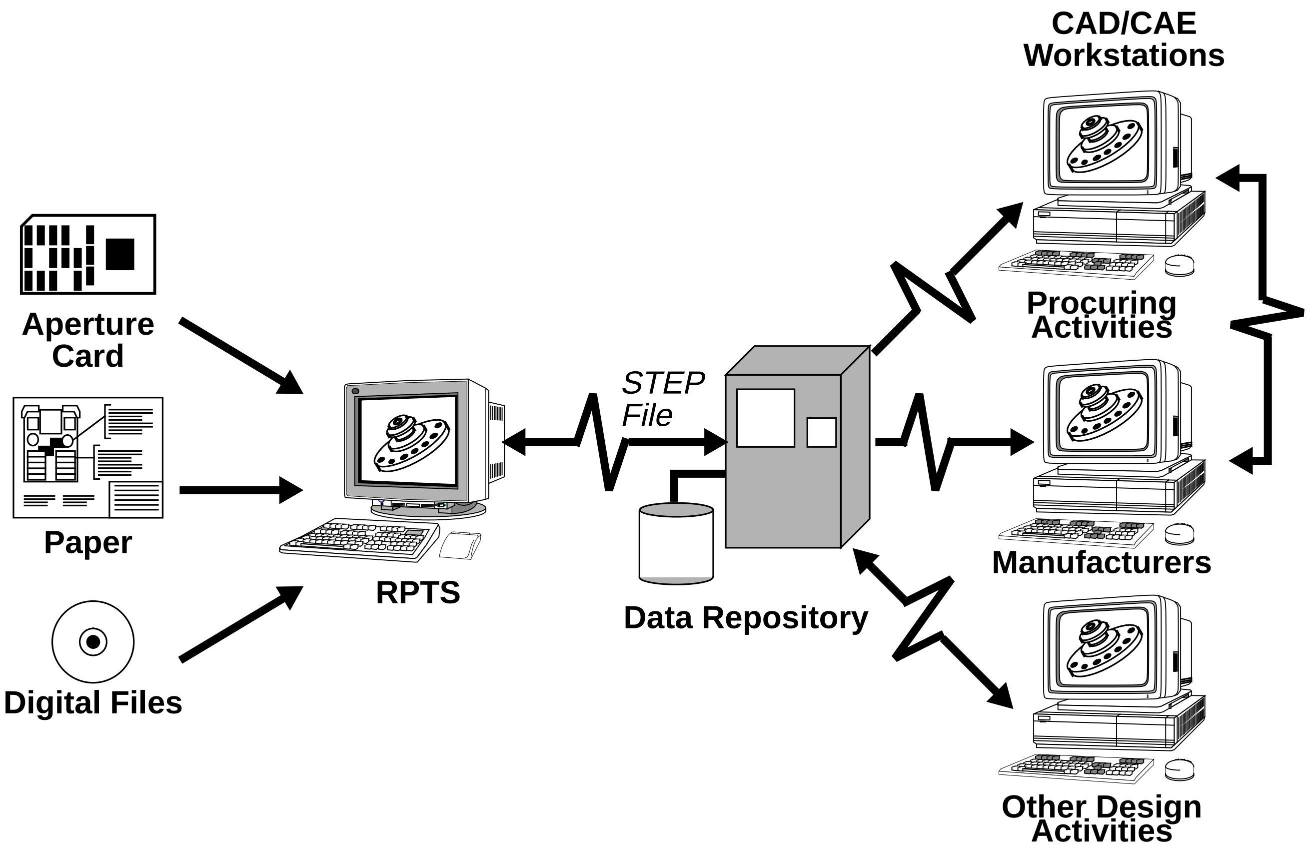

Figure 1 **RPTS MP converts part data to STEP format**†

†. "What is RPTS?", *RAMP-STEP Newsletter*, Volume 1, Number 1, South Carolina Research Authority, September 1993, p. 3.

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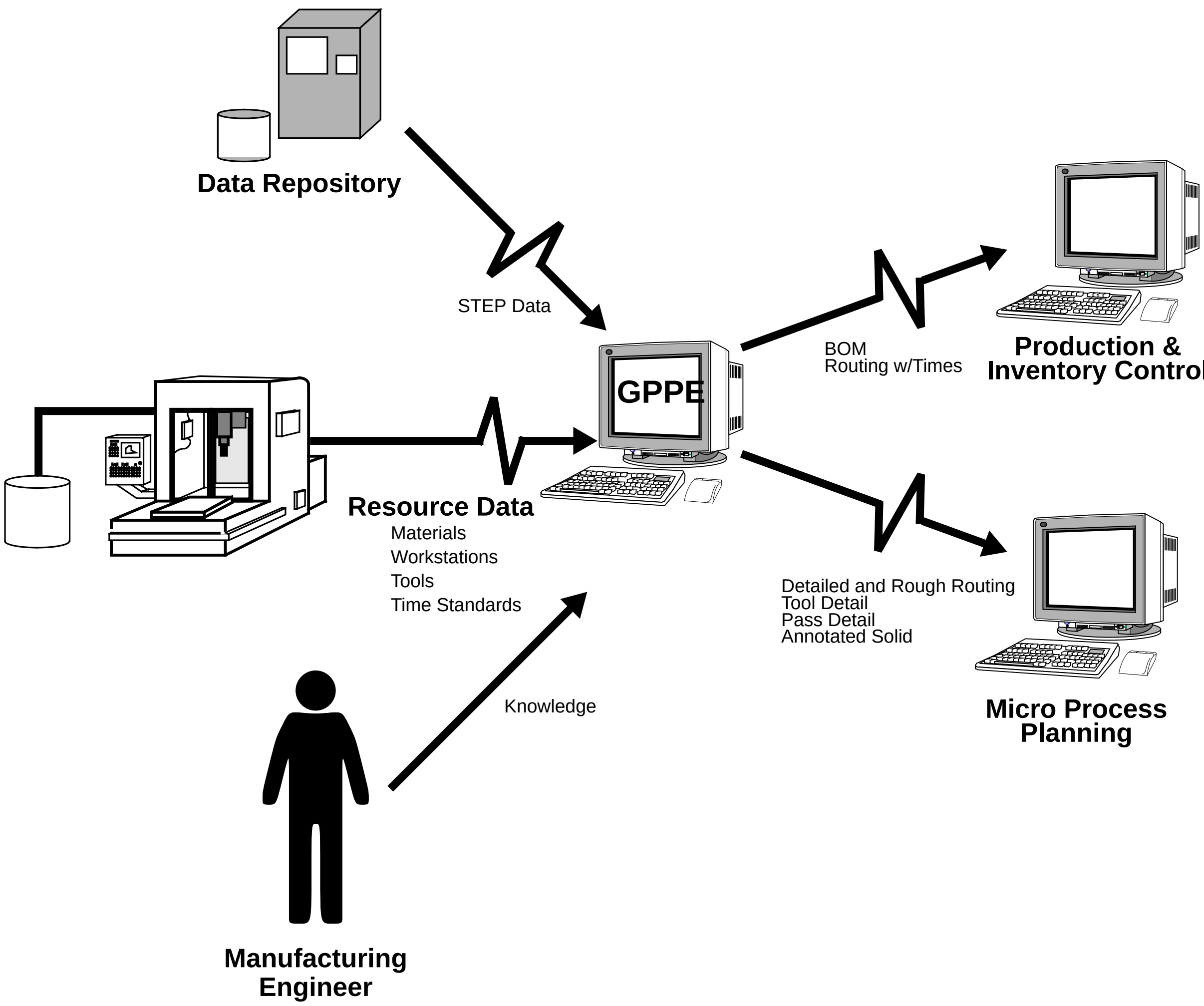

Figure 2 GPPE generates process plans from STEP data†

†. "What is GPPE?", *RAMP-STEP Newsletter,* Volume 1, Number 1, South Carolina Research Authority, September 1993, p. 4.

QTC

The Quick Turnaround Cell (QTC) [28] is an integrated software and hardware system for rapid product prototyping consisting of engineering, workstations, machine tools, and a vision inspection system. Its objective is to study the integration of design, process planning, cell control, and vision inspection. Figure 3 illustrates the system architecture of the QTC. The major elements of the QTC architecture include the design module, the process planning module, and the cell controller module. These modules are tightly coupled and integrated with various knowledge and data bases.

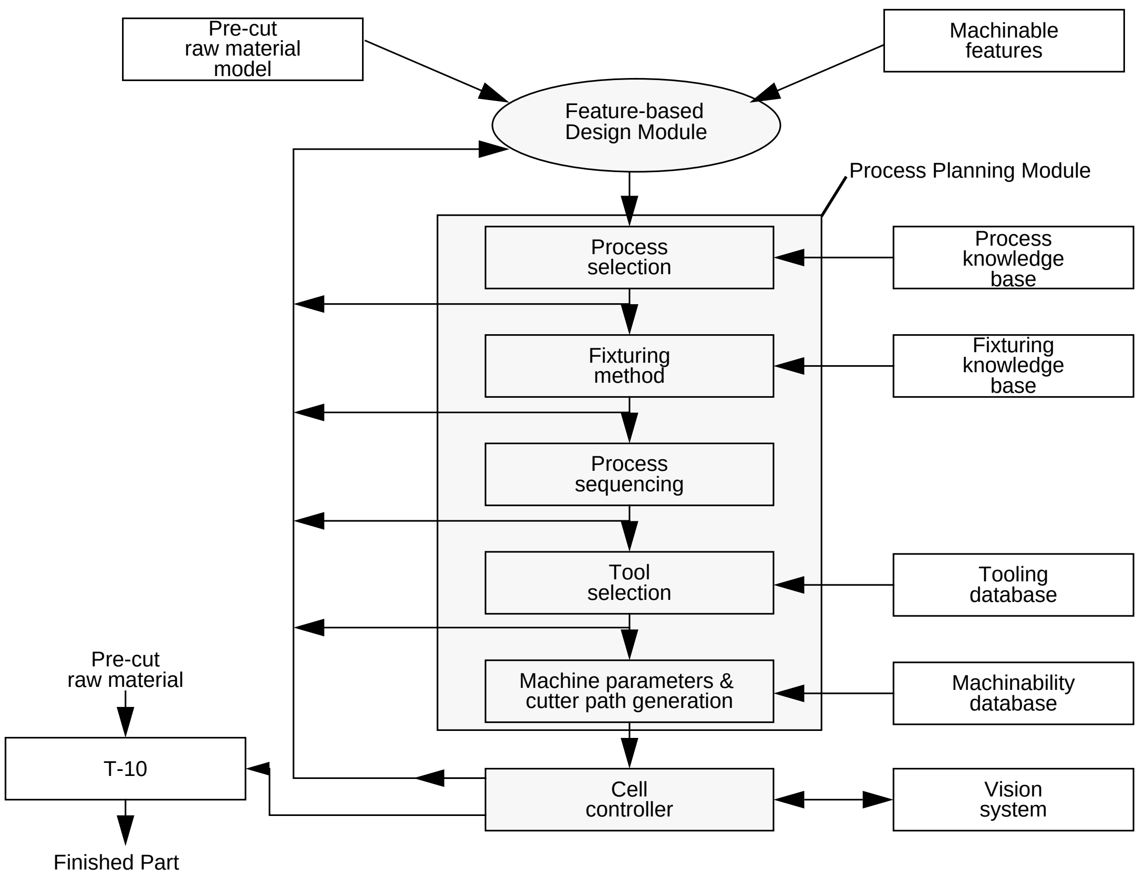

Figure 3 **Overall System Architecture for QTC†**

†. Based upon a figure in Kanumury, M. et al., “An Automatic Process Planning System for a Quick Turnaround Cell -- An Integrated CAD and CAM System,” *Proceedings of the USA-Japan Symposium on Flexible Automation -- Crossing Bridges: Advances in Flexible Automation and Robotics,* Minneapolis, July 1988, p. 862.

The design module consists of a feature-based design system built upon a solid modeler. Inputs from the designer include feature dimensions and tolerances and the raw material stock selected from the raw material database. The part is constructed by removing volumes from an initial part blank. The output of the design module is a part file.

The process planning module performs process selection, tool selection, fixturing, sequencing, machine parameter selection and cutter location (CL) data generation. Inputs include a part file from the design module (which is read in and analyzed in a manufacturing context) as well as data from various knowledge and data bases. The process knowledge base provides input for process selection; the fixturing knowledge base provides input for fixturing selection; the tooling data base provides input for tool selection; and the machinability data base provides input for CL data generation. Output is a detailed process plan with setup information, part orientation and position, tooling information, and operational detail such as machinability and CL data.

The cell controller schedules the part and executes the necessary machining operations. It post-processes CL data and downloads that data to a specific machine.

DFA/CAAPP

Molloy [32] presents an architecture for an integrated design-for-assembly/computer-aided assembly process planning (DFA/CAAPP) system based on feature information.

Figure 4 illustrates the DFA/CAAPP Architecture. It consists of a product model (which accesses an assembly data base and a component data base), a process knowledge base, a DFA knowledge base, a feature-based CAD system, a CAAPP system, component data, process data, DFA software, and DFA knowledge acquisition software.

The architectural elements are linked by a common data management system consisting of a data manager and a data manager interface.The assembly data base stores information related to a particular assembly, and the component data base stores complete information for each component. The process knowledge base contains parameters of the assembly process. The DFA knowledge base contains DFA guidelines.

The data manager allows access to the CAAPP, DFA, and knowledge acquisition systems. Using the same features and component information as the DFA system, the CAAPP system generates assembly sequences of the product based on the disassembly approach. The knowledge acquisition

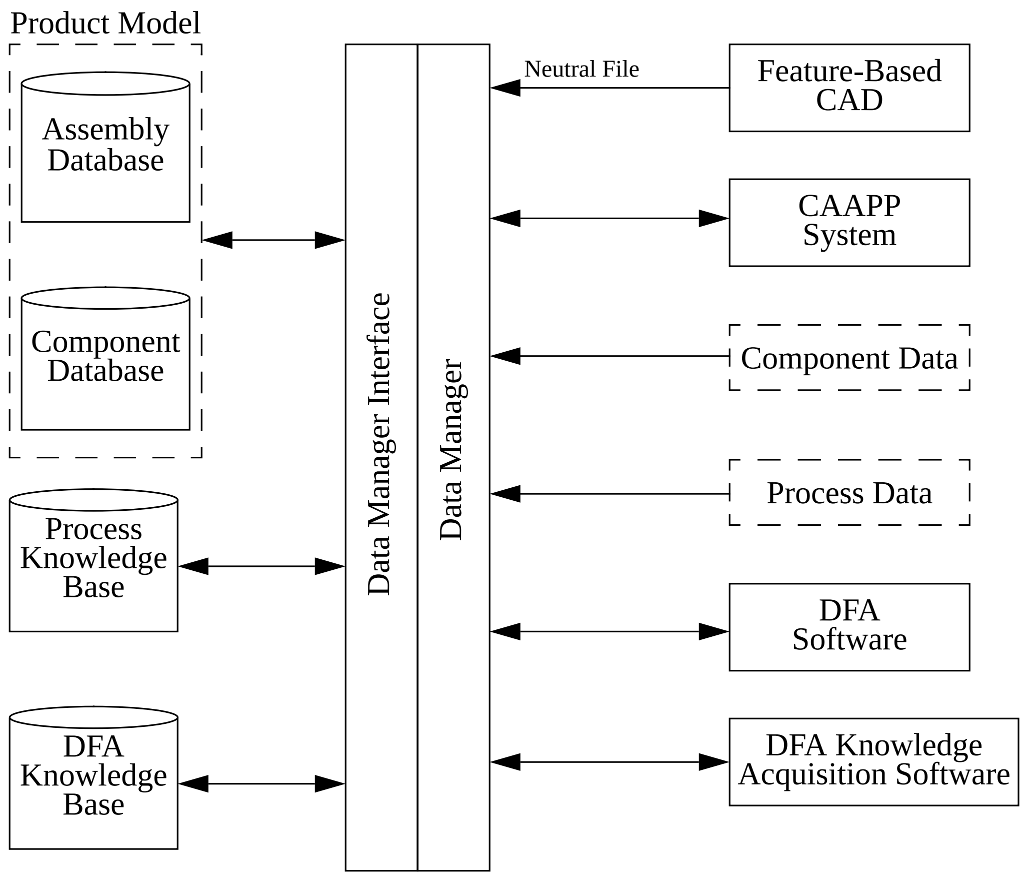

Figure 4 **DFA-CAAPP Architecture†**

†. Molloy, F., H. Yang, and J. Browne. "Feature-based modeling in design for Assembly," *International Journal of Computer Integrated Manufacturing*, Vol.6, No. 1-2, Jan - April 1993, p. 123.

system captures manufacturing expertise in the form of DFA rules based on feature information available from the design system.

KCAPPS

KCAPPS, a Knowledge-based Computer-Aided Process Planning System [42], is an integrated system for design and manufacturing planning. The four major elements of the KCAPPS architecture (Figure 5) are the integrated data base, the user interface, the knowledge base module, and the main module. The integrated data base contains information from various sources. Geometric data and finite element data are retrieved from CAD and CAE data bases. Data required for manufacturing planning (e.g., manufacturing features, tolerances, surface finish) is obtained through KCAPPS' user interface. Design variables, performance requirements, and the results of design sensitivity analysis are obtained from the Design Sensitivity Analysis and Optimization Workstation (DSOW).

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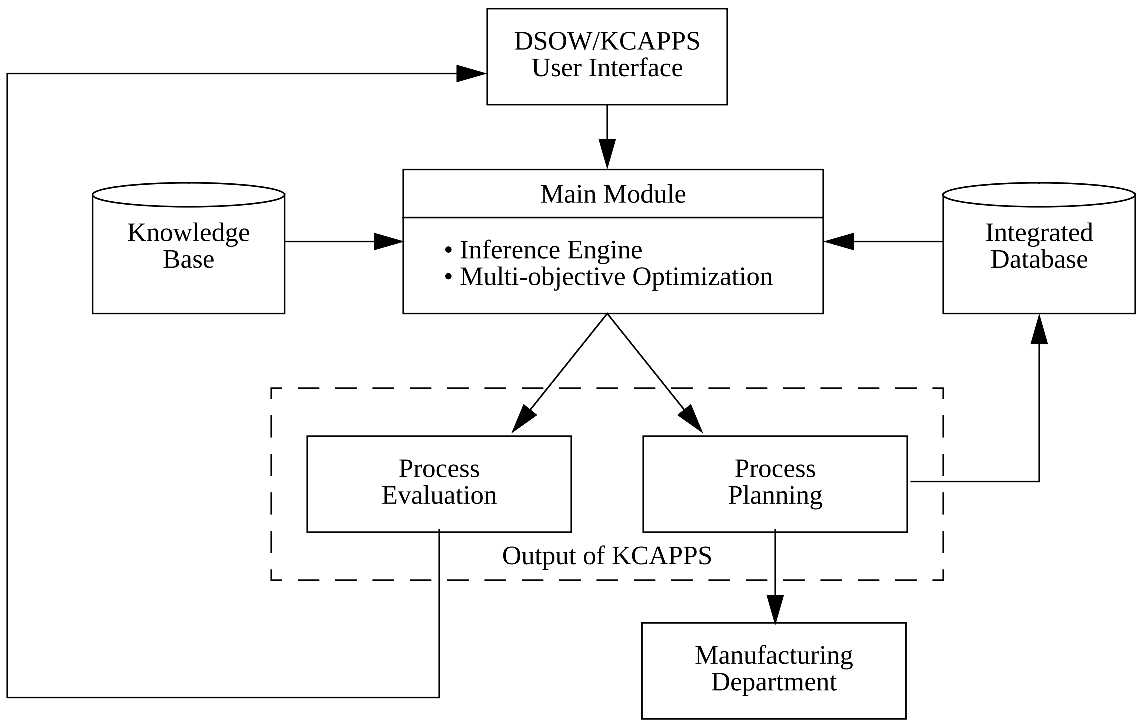

Figure 5 KCAPPS Architecture†

†. Wie, Yui, Gary W. Fischer, and Jose L. T. Santos, "Concurrent Engineering Design Environment for Generative Process Planning Using Knowledge-based Decisions," *1990 ASME Design Technical Conference*, Chicago, Sept. 1990, p. 36.

The knowledge base module provides access to production information. Knowledge bases exist for stock selection, operation selection, machine cell selection, and tool and fixture selection.

The user interface allows the designer to request the manufacturing information associated with a particular feature or complete part during a design session. The interface allows the designer to determine the effects of design parameter changes on production.

KCAPPS' main module provides the mechanism to infer the production rules stored in each knowledge base. Moreover, the main module calculates the optimal values of manufacturing parameters according to a set of empirical equations. The inference engine of the main module makes the following determinations based on previous results and the current knowledge base: shape of stock, manufacturing operations and machine cells, cutting tools and fixtures, and the sequence of selected operations. Finally, the main module obtains the optimal values of the process parameters for either single and multiple performance objectives.

XTURN

Ascribing to a concurrent engineering philosophy, Herman et al. [14] developed a CAPP system that is usable throughout the product development process. XTURN, specifically designed for the planning of turning processes, allows a single engineer to insert manufacturability concerns and known process details in the early stages while postponing more arbitrary decisions to later in the product development cycle. The flexibility of this system supports the dynamic interactions that occur between product and process development activities.

Figure 6 illustrates the architecture of XTURN which includes the following layers: hardware, kernel, knowledge, domain, and application.

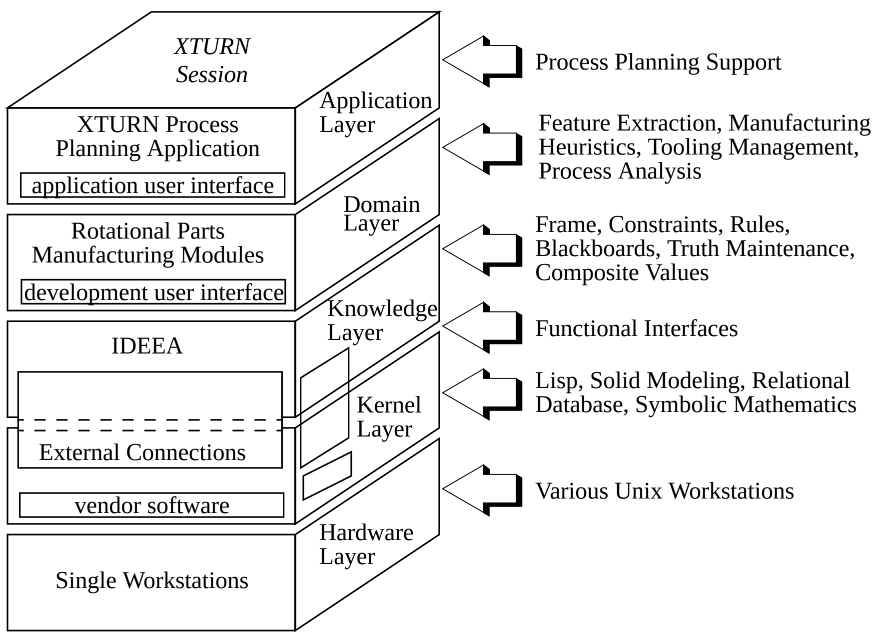

Figure 6 **XTURN System Architecture†**

†. Herman, Allen, Mark Lawley, Stephen C.-Y Lui, and David Mattox, "An Opportunistic Approach to Process Planning within a Concurrent Engineering Environment," *Annals of the CIRP*, Vol.42, No. 1, 1993, p. 546.

The hardware and kernel layers use vendor-supplied products such as computer workstations, compilers, solid modelers, data base management systems, and symbolic mathematics software.

The knowledge layer is based on IDEEA, a decision support environment, which integrates various tools such as solid modelers, finite element analysis software, data base storage schemes with multiple knowledge representations and reasoning paradigms. The use of IDEEA has several advantages for integrating design and manufacturing activities. First, it allows the product and process design effort to share multiple formats of knowledge and data in a context sensitive manner. Second, it allows information exchanged between design and manufacturing activities to be defined at run time by the data and knowledge provided by the engineer. Third, it enables an engineer to specify a family of designs and process plans instead of only a single design and process plan.

The domain layer consists of the following process plan modules: feature extraction, tooling and manufacturing requirements specification, tooling selection, process simulation, turning subplan specification, and tool assembly table generation.

Lastly, the application layer coordinates all the modules from the domain layer to assist an engineer in generating process plans and modifying the product design based on manufacturing concerns.

Summary of Architectures

There are certain elements which are common to all of the integration architectures discussed above. This set of common elements is a good indicator of the minimal ingredients of a design-to-process planning integration architecture. These ingredients include the use of feature-based CAD systems, data bases, and knowledge bases. Although the published level of detail regarding data requirements varies considerably among these systems, some unstated data requirements can be inferred. Design-to-process planning integration requires information about part features (type, location, dimensions, tolerances, orientation, and surface finish), part material (type, mechanical, thermal, and physical properties; and heat, chemical, and surface treatments), and the capabilities and limitations of machines, tools, and fixtures. Additionally, DFA/CAAPP integration requires information about component position and orientation, mating features, and mating operations. It is interesting to note that all of the architectures surveyed adopt the notion of a predefined set of feature types, rather than the ad hoc definition of features. This approach was presumably chosen to allow the use of process planning rules based upon feature type. Finally, to the authors' knowledge, none of the surveyed systems employ geometric reasoning to validate the resultant process plans. That is, any solid modeling or geometric reasoning capability is used during product design, but is not used during process planning to check for feature interaction or feature access.

Information Models

This section reviews two kinds of information models necessary for design and process planning integration: activity models and data models. An activity model describes a process activity and its subactivities, as well as the data associated with the activity. A data model defines data elements and the relationships among them. A data element describes its attributes and relationships (e.g., inheritance, aggregation, classification) to other data elements. Information models specify the context, the application of data, and data definitions.

Activity Models

This section describes activity models in machining, sheet metal working, assembly, and inspection application areas.

CAM-I

CAM-I [9] defined a model which describes the process planning activities for machining. In this model, the activities of generating sets of processing instructions are specified. The data flow and the relationships between specified activities also are described. The following activities are described in this model: analyzing features and tolerances; ordering raw materials; selecting tools and gages; determining machine tools and workstation; ordering equipment; sequencing operations; setting cutting conditions; specifying set-ups and fixtures; and evaluating draft process plans. For planning activity needs, input data are grouped into product definition data (i.e., geometry, material, tolerance, and surface property) and process-related data (i.e., lot size and process capability specification). At output, the model indicates process plans and production scheduling plans. For control data, tolerancing standard and manufacturing analysis rules are indicated.

IMPPACT

A model defining activities and data for planning sheet metal working processes was developed by the IMPPACT project [2] under the European Strategic Program for Research in Information Technologies (ESPRIT). This model describes tasks such as selecting specific manufacturing processes, defining process sequences, estimating processing time, generating NC programs, and preparing documents. The planning activity is supported by a knowledge database for decision making and optimization. The activity model is captured in IDEF-like[2] diagrams. The data model is captured in Nijssens Information Analysis Method (NIAM) [34] diagrams.

AAAP

The Automated Airframe Assembly Program (AAAP) funded by the Air Force Manufacturing Technology Program developed an activity model for airframe design, assembly planning, and inspection planning [12], [31]. Input data include product definition, manufacturing capability, previously developed plans, standards, and procedural guidelines. Output data are NC programs, production plans (i.e., assembly plans and inspection plans), and a report of potential problems. The model is captured in IDEF0 diagrams.

Inspection

An inspection process planning activity model was developed by Feng [8] at NIST. The model defines the following activities: selecting coordinate measuring machines, video sensors, and probes; generating the sequence of inspecting features and inspection paths; selecting and specifying fixturing tools and methods; determining data analysis algorithms; and evaluating and approving draft inspection plans. Input data include product definition, manufacturing plans, and dimensional measurement equipment data. Output is the inspection plan and data structures for interfacing with dimensional measurement systems. Control data include tolerancing and dimensional measuring standards, manufacturing and inspection knowledge, and inspection guidelines. Resource data include planning systems, databases, knowledge bases, and simulation systems. The model is captured in IDEF0 diagrams.

Data Models

Data models specifying data elements and relationships related to product design and process planning are surveyed. The data models described in this section are generated from standards bodies, research organizations, and private companies.

The Standard for the Exchange of Product Model Data (STEP) includes data models for capturing product definitions. These models, which are being developed within the International Organization for Standardization’s Technical Committee 184 (Industrial Automation Systems and Integration) Subcommittee 4 (Industrial Data and Global

2. The U.S. Air Force Program for Integrated Computer Aided Manufacturing (ICAM) developed several IDEF (ICAM Definition) modeling methodologies to graphically characterize manufacturing systems. IDEF0 is the ICAM methodology for producing functional models.

Manufacturing Languages) (ISO/TC 184/SC 4), are defined using the EXPRESS data specification language [15]. The information captured in the models includes generic product information, product structure (assembly), geometry and topology [18], surface condition and material [20], dimensions and tolerances [21], form features [22], process definitions [23], and application protocols (APs). The STEP APs are the specifications which manufacturing applications implement to provide conforming data exchange capabilities.

Manufacturing resource data is not supported by STEP. Several STEP data models have been developed and applied in industry.

MO System

Lapointe, Laliberty, and Bryant developed a process resource model in a Manufacturing Optimization System [30]. The model was created in EXPRESS. The model has a process schema and a resource schema. The process schema defines manufacturing specification, cost, rework, operation, and quality data. The resource schema describes labor, equipment, facility, material, and rate of handling resources. In this system, process knowledge is in the form of “if-then” rules. Rules are used for ensuring producability and optimizing the process with respect to time and cost as parameters or constraints of a manufacturing process for printed circuit board production.

IMPPACT

A manufacturing resource model was also developed in the IMPPACT project [2]. The model is captured in NIAM. The resource model specifies tooling, workpiece, and machine information such as tool properties, tool location, tool life, etc. required by machining processes and stamping processes. The model also specifies the format in which data are exchanged between different application systems.

ALPS

A Language for Process Specification (ALPS) [3] was designed to serve as a generic model to support process plans used within the discrete-process manufacturing industry. The model is based upon a directed graph representation, but is defined in terms of a conceptual model, both in NIAM and in EXPRESS. The design goals for ALPS include the support for task decomposition, parallel tasks, synchronization of tasks, alternative task sequences, resource allocation, critical (noninterruptible) task sequences and information manipulation operatives.

STEP Part 49

A process plan data model is being developed within ISO/TC 184/SC4. STEP Part 49 [23] provides a generic description of a process plan and the relationship with product design. Process planning-related APs for numerically controlled machining, sheet metal working, casting, dimensional inspection, assembly of mechanical parts are also being developed or approved for development.

STEP Part 213

Part 213 [24] specifies an application protocol for exchanging, archiving and sharing numerical control process plans for machined parts among dissimilar CAPP systems. It addresses the relationships that exist between different process plan elements as well as relationships between these data elements and the product definition data such as geometry, surface finish, and tolerances.

STEP Part 214

This application protocol [25] specifies core data for the design of automotive mechanical systems including car body, power train, chassis, and interior components. It defines the context, scope, and information requirements for the mechanical design aspects of the processes of product definition, styling, design, evaluation, production planning (including process planning), tool design, tool manufacturing, and quality control. It also specifies the use of the integrated resources necessary to satisfy these requirements.

STEP Part 224

This application protocol [26] defines the context, scope, and information requirements for the representation of information needed to produce mechanical product definitions for process planning using form features. It specifies the integrated resources necessary to satisfy these requirements which concern part identification, part administration, part property, and part property representation data necessary for the definition of a part for process planning.

Summary of Surveyed Information Models

The information models in this survey include activity models and data models. The activity models were developed for modeling specialized functions, such as machining, airframe assembly, sheet metal working, and inspection. Still missing is an activity model that defines the whole product development process which includes conceptual design, detail design, analysis, process planning, production planning, and quality assurance. A product development model will ensure the connection of all the specialized functions. Such a comprehensive activity model would also provide the scope for defining product and process-related data models. A further discussion of this subject can be found later in this paper.

Interface Protocol Specifications

An interface is a syntactic specification of communication between any combination of the following: software systems, application systems, and database systems. A data model and interface specification facilitate smooth and unambiguous data exchange (but do not ensure full interoperability).

STEP Part 21

STEP Part 21 [16] provides a specification for the encoding of data which has been modeled in EXPRESS. It provides a mapping from the EXPRESS model to an ASCII file format. Using the Part 21 specification, one system encodes and writes the data to be exchanged to a text file, and another system reads and decodes the file into its own native formats.

SDAI

STEP Part 22 [17], which is called Standard Data Access Interface (SDAI), specifies an interface for application programs to access product definition data stored in database systems. Product data can thus be exchanged between application systems through data base access (storing and retrieving).

CAD Interface

Joshi and Chang [27] developed an interface between computer-aided design (CAD) and computer-aided process planning (CAPP) systems. The CAD Interface takes geometric models in both constructive solid geometric (CSG) form and boundary representation (B-rep) form. The CAPP system first determines materials to be removed by comparing the finished part model with the raw material model. The system then identifies machining features and represents them using graphs. A graph contains all the connections between two adjacent surfaces of a machining feature. With identified graphs, the CAPP system generates a machining specification including feasible machining directions, possible fixture configurations, and machining sequences. This CAD/CAPP interface is primarily a machining feature generation mechanism.

CORBA

CORBA [35] defines a client-agent-facilitator architecture for exchanging data and performing services and is unlike previously-described data interchange methods. One system, as a client, sends a request in the predefined format to an agent. The agent finds a system as a facilitator that can provide the service to satisfy the request. After the client processes the request, it sends the message to the agent who then brings the results to the client. The systems exchange data and services through agents in the CORBA architecture.

Key Problems

A rapid response manufacturing environment requires integration mechanisms which allow design and process planning systems to logically share information from a single repository, rather than simply exchange information between these systems. This repository may consist of several data bases, although it is conceptually a single information source to provide for data integrity and prevent redundant data. The integration mechanisms must be flexible to support feature-based and parametric CAD systems as well as interactive, generative, variant, and hybrid CAPP systems. Moreover, these mechanisms must allow the integration of different CAD, CAPP, and data base and knowledge-based systems across heterogeneous platforms with real-time communication of data and messages. Finally, the open system architecture must provide for legacy systems and multiple operational paradigms.

It should be noted that all of what is being discussed here is in the domain of information. Thus, these problems all have to do with some aspect of information technology and its application to manufacturing.

Communication

In the near term, there is a:

- Lack of consensus information models capturing data in common to the two functions (design and planning).
- Lack of communication protocols between the functions. Concurrent engineering work often has relied on computer mediated human collaboration, but has stopped short of formalized protocols.
- Lack of a design/process planning process model, i.e. a characterization of how these functions interact with one another, and what happens when they do. Some might call this workflow management.

Some of these communication needs have been or are being worked on, as described earlier in this paper. One important aspect of the information representation which still needs attention arises in the context of concurrent engineering. In such a scenario there is a cyclic communication between the design and planning functions, with the nature of the information becoming increasingly more detailed and concrete over time. This form of iterative communication requires the ability to represent design and planning information at several levels of abstraction, as well as representing incomplete information. Current work on design and planning representation does not support such representation.

Legacy Systems

Integration of legacy systems is a constant issue. A reasonable approach to address this in the near term involves the use of neutral representations and protocols through which all information passes to and from existing systems. Use of neutral formats avoids the problem of point-to-point translations, requiring only N interfaces instead of N(N-1)/2 interfaces for connecting N systems. In the longer term, even this approach will not solve issues of integration of systems with distinct paradigms.

Knowledge Exchange

In design and process planning, knowledge data is useful and often shared among systems. Knowledge provides the designer and planner with past experience to help optimize the design and process plans. Knowledge data currently is captured in various formats, such as frames and rules. For example, design and process knowledge data interchange formats for concurrent engineering environments have been developed by the PACT project [5]. The development of a standard knowledge representation for process planning is also discussed by Ray [36]. A complete knowledge data model for design and process planning is still needed however, and should be integrated with product and process planning data models.

Software Paradigms

There is a debate concerning which direction should be taken in addressing these problems, specifically what choice of paradigm should be adopted. Should the industry go the route of object-oriented or agent based systems which advocate the encapsulation of data and function within an object? Proponents argue this enhances software reuse and speeds the development and maintenance process. On the other hand, should function and data be explicitly separated? Advocates of this approach argue that regardless of how you manipulate information, facts are facts and should remain intact. This separation allows evolution of systems with new capabilities and ways of manipulating data without altering the underlying data stores. Only the applications are changed.

Both of these points of view must account for the fact that the models of both the data and the functions evolve and that neither can be expected to be correct over time. This fact argues against any notion of a centralized, or possibly even standardized, model of manufacturing data, suggesting instead a standard way of describing and interrogating a model which changes over time, which is an approach more consistent with federated data systems (or object systems).

To summarize, some of the key underlying problems include:

- Near-term standards for data and communication.
- Formal representation of abstract and incomplete data.
- Representation and exchange of manufacturing knowledge.
- Concurrency control and transaction management for distributed systems.
- Data model and functional evolution over time.
- Heterogeneous software paradigms.

A Recommended Approach

In order to make a discussion of key problems and recommended approaches more tangible, it is appropriate at this point to describe, at a functional level, one vision of a fully integrated design and planning environment. Such a system would be composed of all of the design and planning functions, including specification or assessment of geometry, tolerance, manufacturability, setup, tooling, cost estimation, fixturing, performance, stress, and thermal behavior as examples. All of these functions would have a view (in the database sense) of all of the information describing both the product and processes. In addition, each of these functions would have the ability to communicate with any of the other functions by means of prescribed communication protocols in order to carry on a dialogue and to pass control and responsibility to one another. Finally, a system architecture would be layered on top of this communication infrastructure which prescribes appropriate behavior for each functional module, and which defines the structure and nature of the interaction of the modules. The behavior would be characterized by means of process models which capture the sequence of events during the design and planning process. The system architecture definition would be augmented by scenarios of behavior (including exception handling) and control structure definitions (hierarchical, heterarchical or other). It should be recognized that the nature of the design and planning process is itself highly data driven. That is, the strategy used to design and plan a part depends greatly on the characteristics of the part itself. Therefore, the architectural definition would not be one dictating a prescribed sequence of events, but one which would modify priorities and strategy dynamically. An example of an implementation of such an architectural approach can be seen in the blackboard architecture of Barbara Hayes-Roth [13].

Given that many of the problems identified in the previous section raise unanswered questions, a logical conclusion is that research is needed to resolve these issues. Since the issues raised fall into both near-term and long-term categories, different kinds of research and development work suggest themselves.

In the near-term, emphasis should be placed on accelerating a unified effort on the part of industry, government and academia to put in place a series of standard data models and communication protocols to support all of the integration needs between design and process planning. This would include data models for design data, process plan representation, manufacturing resource models in various manufacturing domains, and product life cycle and configuration management data. Some of these data models are already under development as described in this paper. Communication protocols for the dialogue between the design and process planning function are also needed. Before such protocols can be established, a clear process model of how the functions interact must be agreed to, which will establish the scope and domain of the protocols.

To support the longer term problems, more fundamental work should be done to address integration of systems with heterogeneous operational paradigms, and the evolution of distributed data models and system functions over time. Other work on what amounts to operating system theory for distributed systems should be monitored since many of the same issues arise in distributed manufacturing systems. Extension of work in representations to support abstract and incomplete information should be done, which could then feed into the standardization efforts. This research on representations should also extend to the representation and exchange of knowledge. Attention should be focused on architecture implementations exhibiting dynamic strategy adoption. Finally, the connection between technological problems and cultural or business problems cannot be ignored. The adoption of technological solutions must be considered in concert with business reengineering practices underway in many of today's manufacturing enterprises.

Summary

Many of the barriers impeding the integration of design and process planning have been touched upon by one or more projects in the past. This document attempts to provide guidance on what has been accomplished along these lines and, based upon progress to date, what needs to be addressed in the future. The role of NIST in advancing the state of integrated manufacturing should be in enhancing the application of research advances to industrial needs, but is itself a topic outside the scope of this study, and deserves attention in its own right.

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