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INCORPORATING PROCESS PLANNING INTO CONCEPTUAL DESIGN

Shaw C. Feng, Walter W. Nederbragt, Serge Kaing, Ram D. Sriram
Manufacturing Engineering Laboratory
National Institute of Standards and Technology
100 Bureau Drive, Stop 8260
Gaithersburg, MD 20899-8260

ABSTRACT

This paper describes recent developments in the Design and Process Planning Integration (DPPI) project at the National Institute of Standards and Technology (NIST). The project addresses the need for improved communication between design and process planning in the early product design stage. Since major manufacturing costs are committed during product specification and design, it is critical to successfully assess manufacturability and cost as early as possible in the design process. Documenting the DPPI foundation, this paper reviews industry needs for an integrated design and manufacturing environment for rapid product development. Additionally, this paper describes the project's approach and the current status. Conceptual design and process planning prototype systems, that have been implemented, are also described. Finally, it describes the future direction for developing mechanisms to enable the integration of design and process planning, including information models and language interface specifications.

Key words: Conceptual Design, Design and Planning Integration, Information Modeling, Product Design, Conceptual Process Planning, Process Planning, Systems Integration.

1. INTRODUCTION

Errors made during the early stages of design tend to exponentially contribute to the cost of the final product. For example, an error that costs a thousand dollars to fix in the early design stage may require nearly a million dollars to rectify in the production stage. Experienced designers are usually able to create successful initial designs because of their in-depth knowledge of common design practices, customer expectations, and manufacturing processes; however, less experienced designers often require input from experienced designers in all of these areas. Ideally, a designer must be able to access necessary manufacturing, design, and cost information during the design of a product. Even with the recent technological advances in Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), finite element analysis, kinematic analysis, Computer-Aided Process Planning (CAPP), Numerical Control (NC) programming systems, and other Computer-Aided Engineering (CAE) technologies, making sound decisions in the early design phase is still rather difficult since it involves an understanding of many unpredictable factors in manufacturability, quality, reliability, and serviceability [1, 2, 3]. Of these factors, the most substantial ones are the manufacturability of the design and the cost of fabrication.

Considerable research has been done on mapping traditional CAD data on to process planning systems. However, this work has met with limited success. One problem with the current software interfaces and standards is the lack of integration between CAD data output and process planning input. For example, the primary focus of ISO 10303-203, informally the STandard for Exchange of Product model data (STEP) Application Protocol (AP) 203 [4], is the interoperability between traditional CAD systems. While, the focus of STEP AP 224 [5] (whose main emphasis is on machining features) has been on the input to process planning systems. Additionally, most academic research is focused on generating manufacturing features from detailed geometry for unidirectional communication.

To achieve truly collaborative design and engineering, exchange representations of both design and process information must support multiple levels of abstraction for bi-directional (or multi-directional) communication. For example, during the early conceptual design phase, it is important to understand the trade-offs and implications of high-level design decisions. Symbolic descriptions of designs which are not yet defined geometrically can yield enough input to determine many of the characteristics of the manufacturing process underlying "ball-park" cost estimates. Our work addresses the formal representation of such early design descriptions, and their utility in providing input to conceptual planning and manufacturing applications. *The long-term goal of the NIST DPPI (Design and Process Planning Integration) project is to develop systems interface specifications for integrating design and manufacturing throughout the entire product development cycle*. We expect that these specifications will accelerate the standards development for design and process planning software information exchange and for archiving the design process.

The current scope of the DPPI project is on the information exchange between design and manufacturing process planning software systems for mechanical part design and manufacturing. Considerable emphasis is initially being placed on the conceptual stages of both design and process planning. Data modeling, interface specifications, and prototype system development are major tasks of the project. For data modeling, we characterize those data that affect manufacturing process selection – for example, shape characteristics, processes, assembly tolerances, materials, and surface conditions (roughness, hardness, and finish). We also characterize the data fed back from process planning to design, such as lists of processes, equipment, labor skills, and estimated manufacturing costs.

The rest of the paper describes various aspects of the DPPI project. Section 2 provides a review of industry needs. Section 3 describes the current state of development of design and process planning software. Section 4 provides an overview of the project. Section 5 describes data characterization and initial prototype development. Section 6 summarizes our efforts and describes future directions for the project.

2. Industry Needs

The Manufacturing Systems Integration Division (MSID) at NIST held a workshop entitled Design/Manufacturing Integration (DMI) in November 1998. The main purpose of the workshop was to ascertain industry needs and requirements for integrating design and manufacturing software. Participants were primarily technical managers from aerospace, automotive, design/manufacturing consulting services, and software vendors. The participants expressed interests for standards and research in several important areas: improvement and continued development of current design and manufacturing standards; creation of a dictionary for design and manufacturing; interactive references; and tools for knowledge capture and reuse. The participants specifically saw the need for tools that provide a designer with easy access to manufacturing and material data.

Specifically, the following needs were articulated:

- An information infrastructure for design and process planning that aids interoperability development between design and manufacturing applications.
- An expeditious way to create standards. Continue STEP (ISO 10303) development with a modular approach, broader coverage of manufacturing information, and solutions to current accuracy problems with Application Protocol 203.
- New software tools that will allow manufacturability feedback for designers.
- Interactive references that are intuitive to designers.
- Data dictionary that provides definitions on commonly used terms in design and manufacturing.
- Methods for capturing manufacturing process and equipment capabilities for agile commerce.
- A mechanism for industry to share experiences, especially failures, so that industry as a whole can learn from individual experiences.

3. The Current State of Software Development

CAD/CAM systems have been popularly used in manufacturing industry for years. These systems have continually evolved. Traditional CAD systems handle wireframe geometry modeling, solid modeling, constraint representation [8], and feature representation [9]. CAD systems have been recently augmented. The newer systems provide part assembly modeling, tolerance definitions and analysis, and virtual reality capabilities. Researchers are still developing new capabilities for improving these CAD systems. More advanced CAD systems are being proposed and developed in academia. These advanced systems are largely knowledge-based. Hence, they have automated product generation capabilities and access to large-scale knowledge-libraries [10]. In parallel to CAD technology development, CAM technology has evolved from handling prismatic parts (two-and-a-half-axis or three-axis) to parts with free-form surfaces (four- or five-axis machining).

Between design and machining, there are software tools – Computer-Aided Process Planning (CAPP) systems – for machining planning based on part design. CAPP systems [11] are slowly evolving from traditional capabilities (machining volume finding, cutting parameters selection, tolerance analysis and synthesis [12, 13]) to modern capabilities (automated setup planning, interactive feature finding, equipment/tools selection, tool path generation, and machining simulation – see, for example, Technomatix PART). CAPP serves the function of bridging the gap between design and manufacturing.

Although all of these tools can be very useful, they still rely primarily on geometric data. Moreover, they focus on detailed geometry. Currently, many CAPP systems acquire their data via feature recognition of a finished detailed geometric model from a CAD system. The CAPP system must interpret all of the design intent from the solid geometric model. Once the features have been found – a challenging research area – process plans can be created. This mode of operation does not provide any manufacturability feedback to designers. This leads to inefficient product development cycles.

Hence, there is a need for tools that provide feedback to the designer at every design stage.

In conceptual design, some commercial rule-based design systems have been developed that allow routine design tasks to be automated. A designer can program knowledge into these systems to automatically generate a design using various input parameters. Knowledge Technologies International's ICAD and TechnoSoft's AML are commercially available knowledge-based tools that fit into this paradigm. Although these systems can help a designer during the conceptual design stage (especially for routine design), they do not address many aspects of conceptual design, including functional decomposition and mapping from functions to the designed product. The design process has to be coded into the systems. Moreover, only geometry can be transferred into or from the system. Academic researchers have also been developing conceptual design tools for many years. Several different synthesis systems have been implemented [14]. One such system, CONGEN (CONcept GENerator), is a domain-independent knowledge-based system framework that maps an evolving symbolic description of a design into a geometric one [15].

Process planning technology is also evolving as new analysis methods emerge. Process planning research [16] has been focused primarily on machining feature recognition, fixturing and setup parts, and NC tool path generation at the detailed level of process planning. These process planning technologies utilize detailed design data with detailed geometry, topology, dimensions and tolerances, material, and surface conditions completely specified. Only some of the research focuses on process selection [17, 18]. Research and development of commercial software for process selection and cost estimating at the conceptual design stage is still in an infancy stage.

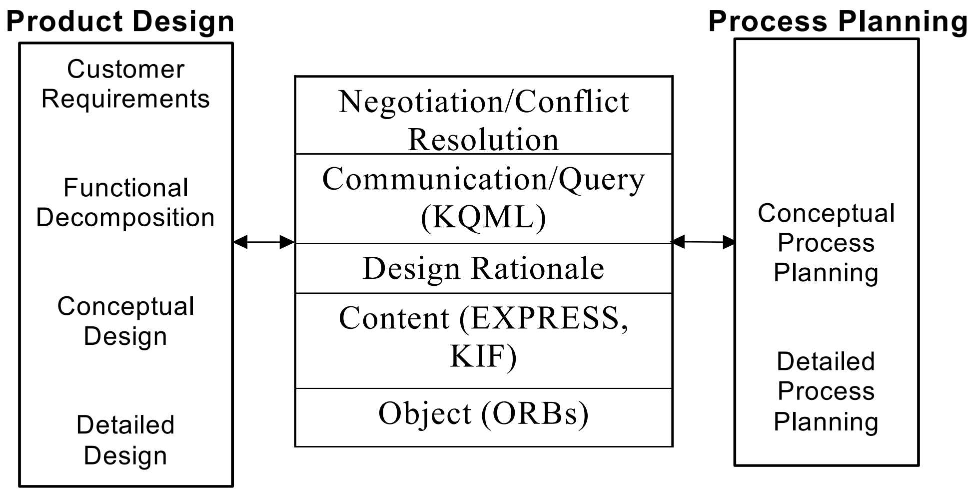
The Systems Integration for Manufacturing Applications (SIMA) program at NIST is addressing issues and developing solutions for interoperability among manufacturing systems. It was initiated as part of a Federal Initiative on High Performance Computing and Communications. The SIMA program is supporting manufacturing system integration technologies; development and testing of interface specifications for manufacturing systems; remote access to scientific and engineering data; and research of collaborative manufacturing environments.

As a result of several projects in the SIMA Program, several information models have been created for various manufacturing applications. A few examples of the diverse work being conducted via the SIMA program are an activity model that describes functions and information flow among design, process planning, and production management [19]; manufacturing resource model for capturing machine, tools, and fixture information for process planning systems [20]; manufacturing execution model to describe production activities on the shop floor [21]; and a Process Specification Language [22] to capture operation sequences of manufacturing processes as an interchange format.

4. Overview of Project

The information exchange between design and process planning applications (and other applications as well) occurs at more than one level. Figure 1 illustrates the many levels of communication that can exist when establishing interoperability between disparate engineering applications.

Figure 1: Communication levels between design and process planning



These levels are described below.

Physical: This level is concerned with the physical transmission media, such as coaxial cable and fiber optics.

Object: At this level, the engineering objects are transported using appropriate object transfer modes, such as CORBA (Common Object Request Broker Architecture) [6].

Content: This level deals with the communication of engineering artifacts, and should include feature, constraint, geometry, material, and manufacturing process. Languages for capturing contents are ISO 10303-11 EXPRESS and Knowledge Interchange Format (KIF) [25].

Knowledge/Design Rationale: This level deals with design rationale and design history issues, which provide additional information (including inference networks, plans, goals, and justifications) about the engineering objects at the Content level.

Communication: This level provides additional detail to the Content and Knowledge/Design Rationale levels. Such details include the specification of engineering ontologies used, sender, recipient, etc., as defined by the Knowledge Query and Manipulation Language (KQML) [7].

Negotiation: Any multi-agent activity will involve negotiation activity. The protocols needed to conduct such negotiations will be defined at this level.

As a part of its commitment to quality in interface-standards development for integrating various manufacturing software, SIMA has adopted a new methodology – called the Initial Manufacturing Exchange Specification (IMES) process – for interface specification development [23]. An IMES provides definitions and exchange protocols of an information exchange format, which serves as a draft standard. The phases in the IMES development process are as follows: (1) identify and define industry need, (2) analyze requirements, (3) design and develop information model and/or data format, (4) validate the model or format with cases from real applications, (5) build consensus, (6) transfer technology, and (7) initiate standardization. These phases were designed to ensure that each IMES would meet industry needs and be suitable for shortening standard development time.

According to the IMES procedures, the DPPI project is in the early stage of the IMES development process. In Phase (1), industry need was defined in the DMI workshop, described in Section 2. The project has started Phase (2) work. An analysis of data and functional requirements are underway. Data include those that are transferred from design to process planning – for example, shape, material, tolerance, surface condition, and product quantity – and those that are transferred from process planning back to design – for example, candidate processes, selected equipment, and estimated manufacturing cost. The design of information models and selection of software systems are also underway. A prototype conceptual process planning system and a prototype conceptual design system are being developed. The rest of the phases will follow after the information models are completed.

5. Project Status

The development of information models and the creation of information exchange protocols that can capture all of the necessary data and knowledge for designs and manufacturing processes are difficult tasks. Therefore, the initial focus of this project is on the communication between conceptual design and conceptual process planning. To understand the various issues involved in developing interface specifications, we selected the problem of gearbox design. We believe that gearbox design/manufacturing information exchange is representative of the discrete-parts manufacturing industry. Using existing software tools and extending available information models, we are concentrating on a particular gearbox configuration. This configuration is complex enough to bring us rich design and manufacturing data, but simple enough for the project to use. We chose to use a planetary gearbox [24].

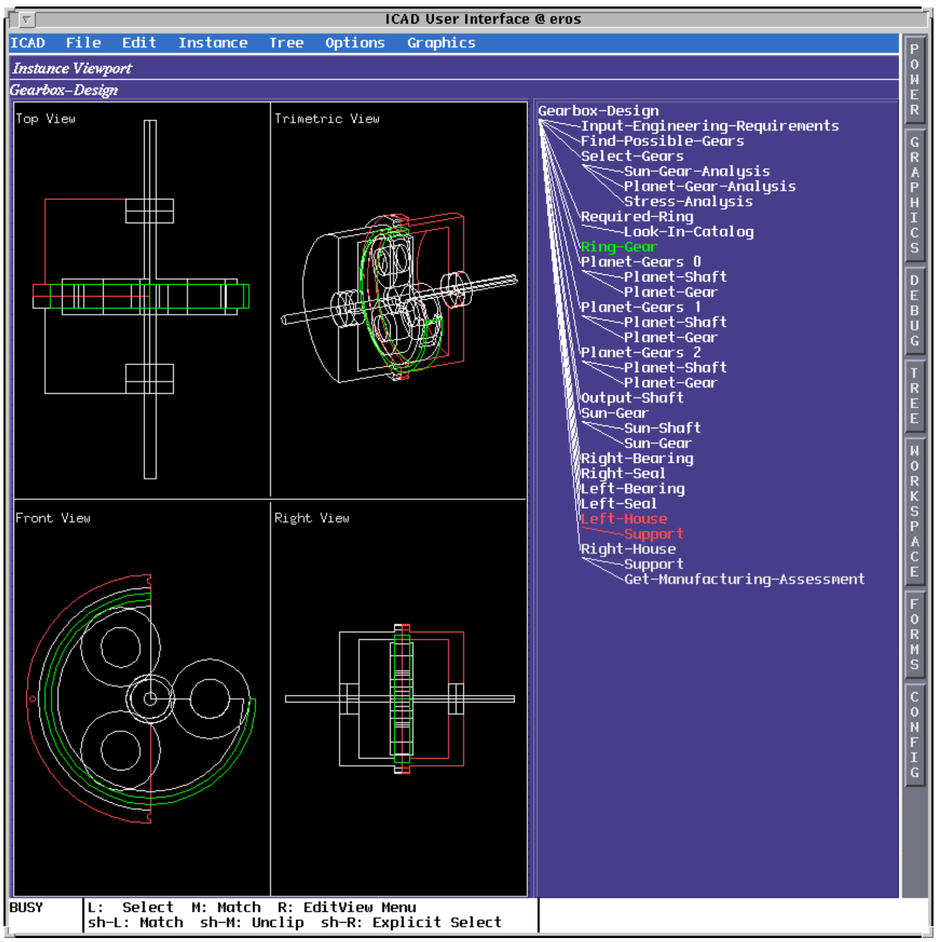
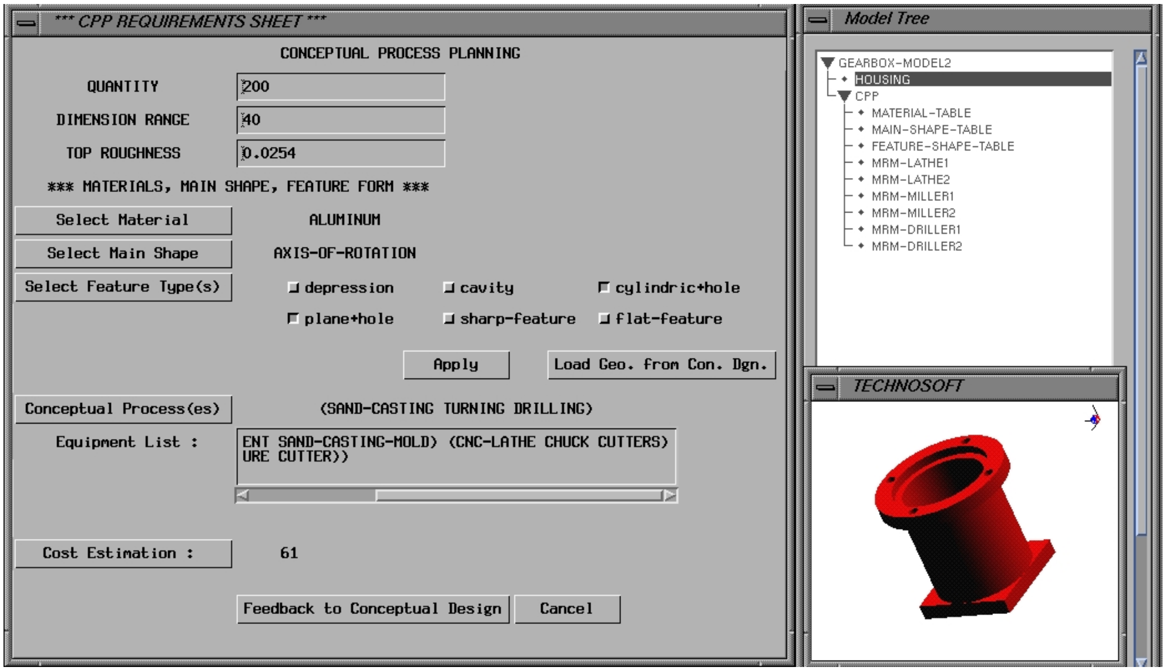


Figure 2: Conceptual design of a planetary gearbox

Conceptual design and conceptual process planning systems are being developed to demonstrate the concept of conceptual design and conceptual process planning integration. They are also used to test the information model and interface protocols that are being developed. Initial system prototypes have been developed, and they are described in the following paragraphs.



The initial conceptual design system prototype was developed using ICAD, which is one of the knowledge-based tools described in Section 3. The functions of this prototype include capturing product functions, describing rough geometry, and listing a bill of materials. The primary functions of a gearbox are to transfer power and reduce speed (or amplify torque) at a fixed ratio. Common gearbox designs contain many components, such as a sun gear, planet gears, a ring gear, an input shaft, an output shaft, bearings, seals, and a housing. Each component has specific functions. For example, a shaft must sustain torque, gears transfer rotational motion and torque, bearings provide the interface between a rotational shaft and a stationary housing to reduce friction, seals provide isolation between gears and the environment, and a housing provides protection and an operational environment for the other components. Our prototype has a design database for designers to select product components. The database provides information on standard parts, engineering material properties, design features, etc. The system also contains design rules that are applicable to planetary-gearbox design. These rules help designers to convert functions to real part design using the design database. Figure 2 shows the graphical user interface for our system. Components are shown in the left window and the bill of materials is shown on the right. We are expanding the design database and rules to aid in the design of other products.

The initial conceptual process planning prototype system was developed in AML, which also is one of the knowledge-based tools described in Section 3. The functions of the prototype include selection of candidate processes, equipment selection, and rough manufacturing cost estimation. To facilitate process planning, the prototype contains process and equipment selection rules and a cost model. Process selection is based on component shape, material, tolerances, production quantity, and surface conditions. Based on selected processes, a list of equipment and labor skills is selected. Production time, material quantity, and manufacturing costs are estimated and reported to the design system using this information. Figure 3 shows the graphical user interface for the conceptual process planning system; it is being used to evaluate a gearbox housing.

Figure 3: Conceptual process planning of the gearbox housing

Assertions	Material	Cast Irons
	Quantity	> 100
	shape	complicated shape
	features	Internal passage, Uniform wall, Differing section size, Undercut, Cavity, Complex contour
	Dimensional characteristics	Section thickness from 3 mm up
	Tolerance	+/-0.6 ~ +/-6 mm
	Surface finish	5 ~ 25(μm)
Result	Process	Green-Sand Casting, Dry-sand casting

Figure 4: Example of a process selection rule

Process and equipment selection rules are an essential part of the conceptual process planning system prototype. The format of the rules consists of two parts: assertion(s) and result(s), as shown in Figure 4. The rules are used to select appropriate manufacturing processes used to fabricate a part with certain production quantities, shape characteristics, tolerances, materials, and surface conditions. Based on the selected processes, manufacturing equipment – including machines, fixtures, and cutters – are selected.

The initial prototypes have helped us demonstrate various issues in design and process planning integration. We have characterized information to be transferred from design to process planning in the conceptual design stage. The data are in the following categories: processes, shape, material, tolerance, and surface finish. Processes include these major subcategories:

casting, metal forming, plastic forming, machining, ceramic forming, joining, and surface treatment. Materials include the following subcategories: metallic (ferrous and nonferrous) and nonmetallic (plastic, plaster, glass, ceramic, etc.). Tolerances are numerical data that processes are capable of obtaining. Surface finish includes data that processes are capable of achieving. The information that is fed back from process planning functions to design include lists of candidate processes, lists of selected equipment, and estimated manufacturing costs. Currently, we are transferring information between our conceptual design system and conceptual process planning system via simple ASCII code. This is due to a lack of information exchange mechanisms in the currently available software packages.

Based on our two prototypes and research into design and process planning integration, several important observations can be made:

- Current knowledge-based conceptual design tools are useful for routine design, but their ability to handle new conceptual designs is limited. Moreover, there is a lack of communication mechanisms for transferring information between these tools.
- Commercial CAPP systems focus on unidirectional transfer of detailed geometric data.
- CAPP research is still heavily focussed on feature recognition.
- Current research in conceptual design and process planning is restricted to academic environments. We hope that some of their systems will be used in this project.
- There is a need for conceptual design and manufacturability analysis tools.
- For the above tools to work, they must be able to interoperate.

Using these observations as a foundation, we are developing an object-oriented information framework for transferring design and process planning information [15]. This framework allows for multiple versions of parts; relationships containing function, form, and behavior for each part; part attributes; constraints; and assembly relationships. We believe that many of the problems found in current integration models can be improved by using this new framework (or parts of it). We are currently applying this framework to the gearbox model to help refine the framework for use in larger design and process planning domains.

6. Concluding Remarks and Future Work

In this paper, the goal, purpose, needs, and the status of the NIST DPPI project are described. Conceptual design and conceptual process planning are identified as two fundamental activities. The conceptual design activity defines initial product functions, shape, materials, and necessary tolerances. The conceptual process planning activity assesses manufacturability and estimates the manufacturing cost of the concept of a product developed in the early design stage. These two activities should be tightly integrated to assist designers to develop better products in a timely manner. The DPPI project is addressing industry needs for the integration of design and process planning activities and functions. Initial prototype systems have been developed to test the concept of transferring design information to process planning and transferring process plans back to design for manufacturability assessment. Conceptual design data have been characterized. Planning rules have been developed. Information models are being developed.

Further development of the integration idea is necessary. Future work includes the following tasks: (1) extending the prototypes using more industrial cases, (2) specifying interfaces for conceptual process planning software, (3) formally representing manufacturing process knowledge, (4) improving cost estimating methods to increase accuracy, and (5) developing an initial specification for information sharing between design and process planning according to the NIST Initial Manufacturing Exchange Specification development procedure [23]. The IMES work includes forming an interest group with members from industry, documenting and releasing the interface specification, transfer prototype technologies to companies for commercialization, and starting standardization process.

During the next year, we plan to obtain a state-of-the-art knowledge-based system to improve our current prototypes. Using our object-oriented framework, we will implement a more advanced information exchange mechanism. We also will extend our gearbox model to incorporate a more generic modeling environment. This work should give us the background necessary to specify, with the help of software vendors, the interface requirements for next-generation CAD and CAPP systems.

Disclaimer

No approval or endorsement of any commercial products by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper in order to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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