Standards for the Collaborative Design Enterprise
Response to Object Management Group's (OMG) MfgDTF RFI#4
URL: http://www.omg.org/homepages/mfg/mfgppe.htm#PPE RFI

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1. Introduction

Design of complex engineering systems is increasingly becoming a collaborative task among designers or design teams that are physically, geographically, and temporally distributed. The complexity of modern products means that a single designer or design team can no longer manage the complete product development effort. Developing products without sufficient expertise in a broad set of disciplines can result in extended product development cycles, higher development costs, and quality problems. On the other hand, ensuring comprehensive technical proficiency in a world where trends are toward more multidisciplinary design can become a costly undertaking for a company.

Driven by such issues, companies are increasingly staffing only their core competencies in-house and depending on other firms to provide the complementary design knowledge and design effort needed for a complete product. Designers are no longer merely exchanging geometric data, but more general knowledge about design and the product development process, including specifications, design rules, constraints, and rationale. Furthermore, this exchange of knowledge more and more often crosses corporate boundaries. As design becomes increasingly knowledge-intensive and collaborative, the need for computational frameworks to support product engineering in industry becomes more critical.

In this paper, we discuss the various standards needed to realize an effective and agile collaborative design environment. In the next section (section 2), we present a likely scenario for collaborative engineering. In this scenario we envision several categories of computer-aided design/computer-aided engineering (CAD/CAE) applications interacting with each other. We discuss these categories in Section 3. Section 4 outlines the interface specifications relevant for seamless interoperability among various applications. We explore the role of design repositories in collaborative design, including the need for standard representations, in Section 5. Section 6 briefly touches upon product data modelers. In Section 7, we present several abstract use cases to illustrate the ideas presented in the paper. Finally, we provide a brief summary of several ongoing research activities at NIST.

2. A Collaborative Design Framework

Recent trends in computing environments and engineering methodologies indicate that the future engineering infrastructure will be distributed and collaborative, where designers, process planners, manufacturers, clients, and other related domain personnel communicate and coordinate using a global web-like network. The designers may be using heterogeneous systems, data structures, or information models, whose form and content may not be the same across all disciplines. Hence, appropriate standard exchange mechanisms are needed for realizing the full potential of sharing information models. The various applications are coordinated by a work flow management system using a product realization process (PRP); the work flow management system acts as a project manager. They are connected to one another by a design net, which provides the infrastructure for high bandwidth communications. These applications retrieve design data and knowledge from distributed design repositories and the evolving design (or designs) is stored in a database. This database provides various snapshots of the evolving design, with design artifacts and associated design rationale stored at various levels of abstraction. Finally, design applications communicate with other manufacturing applications through various nets, such as production, process planning, and user networks (see Figure 1).

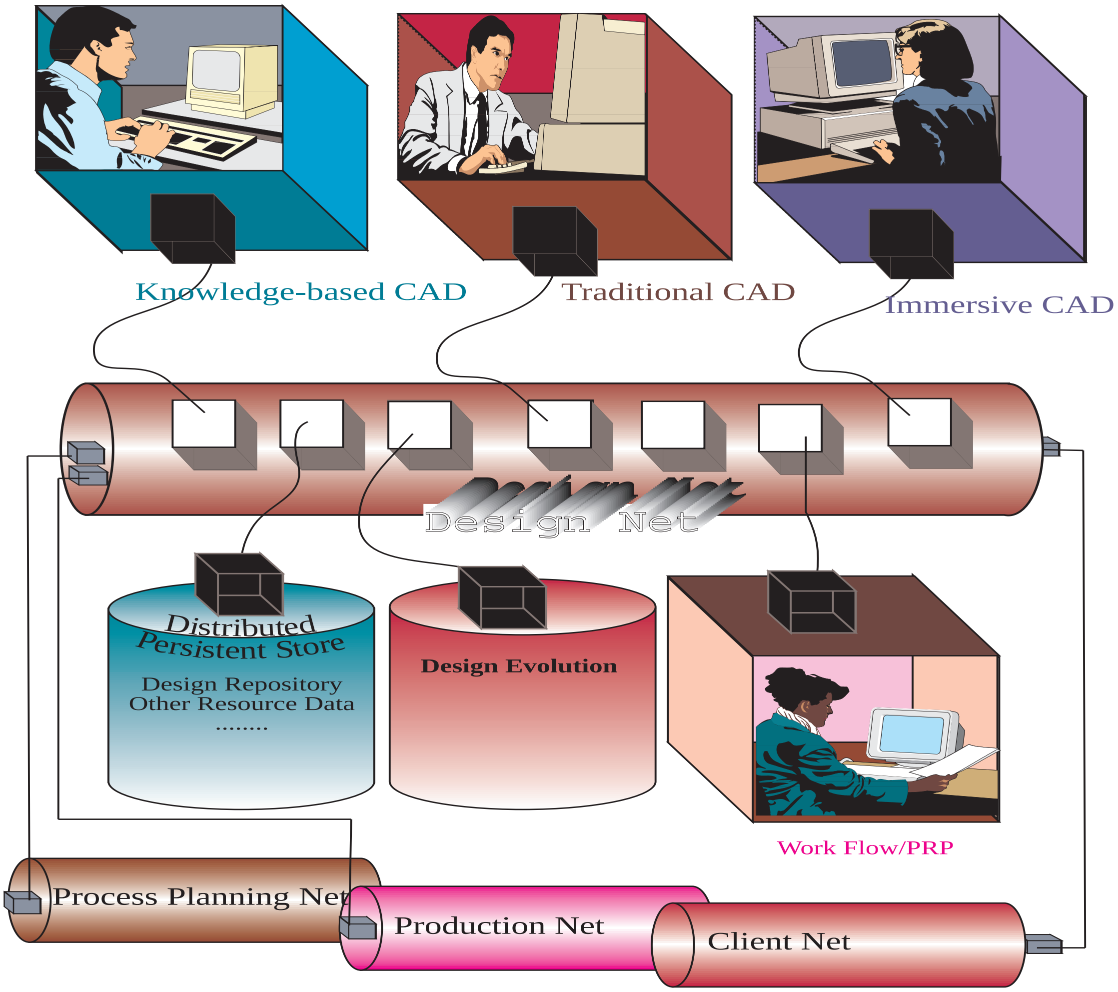

Figure 1**: A Collaborative Design Framework**

3. Computer-Aided Design (CAD) Application Categories

To successfully implement a computer-supported collaborative design environment, we need to address four areas: 1) applications; 2) standards; 3) infrastructure; and 4) organization.

The primary emphasis in this document will be on interoperability standards between CAD applications and interface standards between applications and design repositories. We set the stage for the discussion of various CAD applications by enumerating the various design phases, taken from *Barkmeyer, E. (editor), SIMA Reference Architecture Part 1: Activity Models, NISTIR 5939, National Institute of Standards and Technology, December 1996.*

1: Plan Products

Depending on (potential) market needs and customer requirements, develop the idea for a product and characterize it in terms of function, target price range and relationship to existing products of the manufacturing firm. Define cost constraints, performance constraints and other marketability factors. Perform market analysis and cost-benefit analysis. Develop product development and marketing plans.

2: Generate Product Specifications

From the conceptual product specification, formulate an engineering specification for the product. This involves mapping the customer requirements into engineering requirements, and refining the engineering requirements in consideration of the relevant laws, regulations, product standards, etc., and also of the existing patents in the same area. This process may involve determination of the relationship of the new product to the firm's library of existing product designs.

3: Perform Preliminary Design

Decompose the design problem into a set of component design problems and develop the specifications for each component problem. Define the integration of the components into a product and develop a preliminary layout model. This process will be somewhat iterative, as the early phases of the component design will generate new considerations and changes. Primary results are the product layout drawing and annotations and the component design specifications

4: Produce Detailed Designs

For each subsystem (or component) that is not off-the-shelf (or identical to an existing in-house design), and for the component integration, produce all specifications needed to completely describe the subsystem for manufacture. This includes drawings and geometry, materials, finish requirements, fit requirements and assembly drawings, tolerances, and other relevant information.

CAD applications supporting design, particularly the third and fourth phases listed above, can be categorized into three types -- traditional, knowledge-based, and immersive.

Traditional CAD systems evolved out of an attempt to provide better drafting aids. In these systems, the designer uses a computer to develop either 2D or 3D models of the design. Traditional CAD systems (such as Pro/Engineer) provide comprehensive tools for generating geometric forms, which encourages designers come up with a form first and think about function later (i.e., *form-to-function transformation*). However, this approach can result in non-optimal and non-competitive designs. Closely related to traditional CAD systems are traditional computer-aided engineering (CAE) packages which primarily focus on analysis, in particular finite element analysis.

Tools for helping a designer think in terms of function need to be developed; form should subsequently result from function (i.e., *function-to-form transformation)*. Knowledge-based design systems implement this paradigm by first focusing on the symbolic aspects of design and later mapping the symbolic structure to a geometric model. They can also capture the various semantic relationships between design objects. Essentially, knowledge-based systems use techniques developed by artificial intelligence researchers to capture the knowledge of expert designers in a computer.

In immersive CAD applications, the human being becomes part of the design by using various immersive environments, including haptic, visual, and speech interfaces. Immersive CAD systems can aid in evaluating manufacturability of designs.

In summary, traditional CAD systems require the designer to completely specify all geometric details, while knowledge-based systems aid in the design generation, and immersive environments allow a designer to interact with and become immersed in the CAD world. With regard to the SIMA design activity model, traditional CAD systems and associated analysis programs (typically called computer-aided engineering or CAE) are used in the detailed design phase, knowledge-based CAD systems primarily assist in the preliminary design phase, and immersive CAD systems can aid in both preliminary and detailed design phases.

4. Standards

CAD applications generally do not use the same format for data input and output. For example, Boeing's customers require that it use engines from different manufacturers, such as GE, Pratt and Whitney, and Rolls Royce. Boeing uses CATIA as the CAD tool, while the suppliers use different CAD systems. Each of these systems has its own unique data format and interoperability is a major concern.

We illustrate the interoperability issue by considering a potential information exchange scenario during the design of the Boeing 777.[1] For Boeing to incorporate Rolls Royce engines into the design, the data format has to be converted from Computer Vision’s CADDS (used by Rolls Royce) to Dassault’s CATIA. Similarly, for Rolls Royce to understand changes made by Boeing engineers, the data need to be converted from CATIA to CADDS. Hence, we need at least *2* translators. For three systems this grows to *6* translators and for *n* systems we need *n(n-1)* translators. A solution to this problem is to use a neutral format and make all the CAD applications to output into this format. Doing so will reduce the number of translators to *2*n*, i.e., for each CAD system we will need two translators –- one from the CAD system to the neutral format and the other from the neutral format to the CAD.

A standard of primary interest to design is ISO 10303, also known as informally as STEP (Standard for the Exchange of Product model data) and developed by the International Organization for Standardization (ISO) TC 184/SC4. Its intention is to enable the exchange of product model data between different modules of a product realization system, or the sharing of that data by different modules through the use of a common database. The first parts of STEP to achieve International Standard status were published in 1994, but many other parts have since been published or are under development and will eventually be

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[1] The design and manufacture of Boeing 777 is well documented in the Public Broadcasting Service’s Twenty-First Century Jet: Video and Book Collection, Item Number: C2375-WEBHV.

added to the standard. Recent updates (and other relevant details) can be found at the following website: http://www.nist.gov/sc4.

ISO 10303 (STEP) can be viewed as consisting of several layers. The top layer consists of a set of applications protocols or APs, which address specific product classes and life-cycle stages (e.g., mechanical, electronic, ships, automotive, design, process planning). These application protocols specify the actual data exchange standards and are given the 200 series of numbers. The APs are constructed from a set of modules called integrated resources, which are common for all disciplines. Integrated resources are given the 40 series and the 100 series. The actual transfer of data is achieved in several ways, described by Parts 21 through 26. The language for modeling various STEP entities and their relationships is called EXPRESS. The testing methodology and various test suites comprise the conformance testing methodology framework, which are given the 30 and 300 series numbers, respectively.

The STEP AP most relevant to traditional CAD systems is called AP 203 and is entitled “Configuration Controlled 3D Designs of Mechanical Parts and Assemblies.” This protocol defines the data exchange of geometric entities and configuration control of products. AP 203 defines several levels of implementation –- called conformance classes –- which deal with increasing levels of sophistication. The original proposal had six conformance classes. A recent update splits each of the conformance classes into two (i.e., a and b), and hence there are 12 conformance classes. CAD vendors who are STEP-compliant, are required to indicate the classes to which they comply. For example, a CAD vendor -- selling CADx -- may claim that CADx conforms to Class 6, which means it can deal with advanced BREPS (Boundary Representation).

However, the current emphasis of STEP AP 203 is on shape description plus product configuration data. Facilities have been provided for capturing, in standard format, the following representations: 2D drawings, 3D wireframes, surface models, and solid models. This reflects the state of CAD technology as it was when the STEP development effort commenced in the mid-1980s. However, CAD technology has progressed since that time, and most major CAD systems now provide facilities for parametric, variational (including constraints), and/or feature-based design. In addition many of these systems have facilities to record design histories. These systems generate additional information, beyond the pure shape descriptions created by older systems, and STEP currently provides no means for capturing and transmitting this additional information. The short term parametrics effort (which comes under Working Group 12 of ISO TC 184/SC4) is addressing this problem.

There is another STEP application protocol – Composite and Metallic Structural Analysis and Related Design (AP 209) -- that deals with the data exchange between traditional CAD systems and analysis (such as finite element) applications. AP 209 is aimed at integrating finite element analysis programs with design. In addition to product design and configuration data (which is the scope of AP 203), AP 209 includes finite element (FE) data including meshing analysis controls, static stress analysis results and can deal with polymers and composite structures. AP 209 has recently been approved for publication as part of the international standard.

Below, we summarize the various protocols involved in the interoperability between various types of CAD systems and between CAD systems and manufacturing software. Figure 2 shows a schematic view of various interactions, where all communication is routed through two types of information bases: one local to the design applications, and the other acts as an interface between design and manufacturing applications. Also note that the arrows in the figure indicate a two-way communication between various applications.

Between traditional CAD systems. The various extensions that could be used with AP 203 would include exchange of feature, constraint, parameterization, and design history information.

*Between CAD systems and analysis packages***.** This would involve a mapping from CAD data to a neutral representation for input to an appropriate analysis package. The neutral representation can be based on AP 209, with possible extensions, such as DT_NURBS (Extensions to Non-uniform Rational B-Splines developed by Boeing for the David Taylor Research Center).

*Between knowledge-based design systems and traditional CAD systems***.** Knowledge-based design tools concentrate on the generation of a symbolic structure, using various types of objects and relationships. Mapping from this symbolic structure to traditional CAD will need appropriate interface specifications.

Between traditional CAD and immersive CAD systems. Immersive CAD systems generate certain process constraints, such as trajectory and assembly mating constraints. The interface between immersive CAD and traditional CAD systems requires extensions to appropriate STEP standards, such as Part 42 (Geometric and topological representation), Part 44 (Product structure configuration), and AP 203.

The above protocols address intra-design interoperability. Research on the interfaces between design and manufacturing (i.e., inter application interoperability) could include the following:

Solid interchange format for Layered Manufacturing (SIF-LM). This task involves the use of STEP's generic resources for the development of a standard for the exchange of CAD data with Rapid Prototyping systems, developed for producing physical structures in layers (e.g., 3D Printing).

Between CAD systems and assembly planning systems. This task involves the development of exchange standards for data interchange between traditional CAD systems, immersive CAD systems, and assembly process planning; for clarity's sake we show only the interface between traditional CAD and assembly planning. Representative data would include the creation of trajectory, component orientation information (process data), swept volumes, and assembly sequencing data that can be merged with part representation.

Between CAD and process planning/manufacturing systems. Considerable research has been performed on mapping traditional CAD data on to process planning systems. However, this work has met with limited success. One problem with the current standards is the lack of integration between CAD data output and process planning input. For example, the primary focus of STEP AP 203 is the interoperability between traditional CAD systems, while the focus of STEP AP 224 (Mechanical product definition for process plans using machining features) has been on input to process planning systems. To achieve truly collaborative design and engineering, exchange representations of both design and process information must support multiple levels of abstraction. For example, during the early conceptual design phase (essentially a knowledge-based activity), it is important to understand the trade-offs and implications of high-level design decisions. Symbolic descriptions of designs that are not yet defined geometrically can yield enough input to determine many of the characteristics of the manufacturing process underlying ball-park cost estimates.

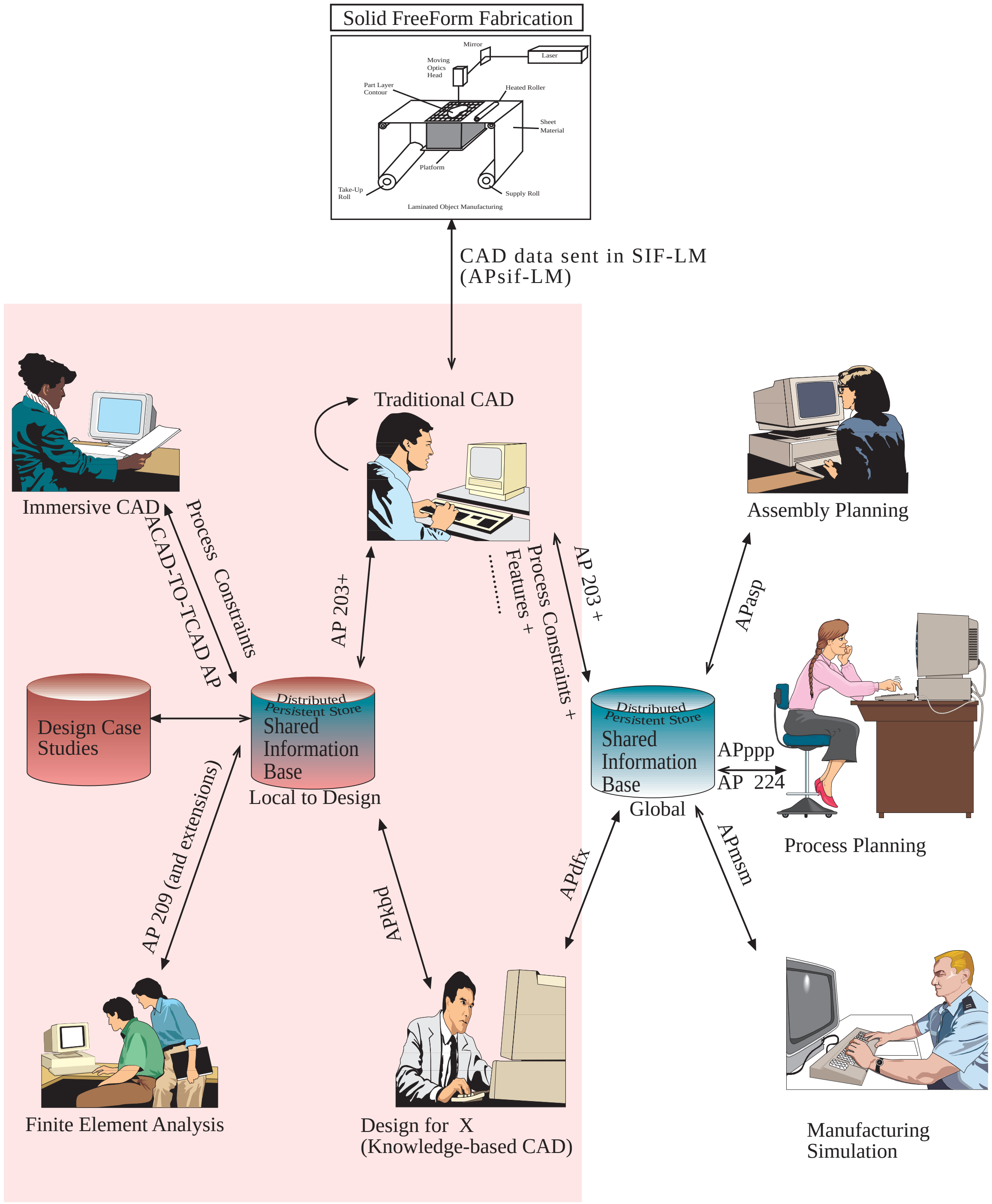

Figure 2: Interfaces between various CAD systems and between CAD and manufacturing software

5. Design Repositories

During the design process, engineers require access to various kinds of design information. Merely providing access to schematics and CAD models of artifacts is inadequate for this purpose. In order to support reuse of engineering knowledge, a representation must convey additional information that answers not only "what?" questions about a design, but also "how?" and "why?" questions. The emerging research area of design repositories is aimed at addressing these industry needs. Design repositories make use of research in knowledge-based design to facilitate the representation, capture, sharing, and reuse (search and retrieval) of corporate design knowledge. It should be noted that although the term *design repositories* has not yet found its way into daily usage in industry, many companies are migrating from traditional design databases to design repositories. While companies may still be referring to their corporate knowledge stores as design databases, in many cases these stores would fall under the definition of design repositories as characterized in this paper. Although design repositories can in general terms be thought of as design databases, and indeed will most often be implemented using database management systems, design repositories are distinguished from traditional design databases in several significant ways:

- Traditional design databases are typically more data-centric than knowledge-centric, and contain only a limited representation of an artifact such as drawings and/or CAD models, version information, and often related documentation. Design repositories attempt to capture a more complete design representation that may include characterization of function, behavior, design rules, simulation models, and so on. It should be noted, however, that a fully comprehensive representation of every aspect of a design may simply not be possible.
- Design databases are generally more homogeneous in the kinds of information they contain. In addition to containing images (drawings), file pointers (to CAD models), and unstructured text (documentation), design repositories may contain formal data/information models, structured text (specialized languages for representing function, design rules, logical expressions), mathematical simulation models, animations, video, and other types of information.
- Design databases tend to be static sources of information (though their contents may grow with time). While they are used for storage and retrieval of design data, capabilities for supporting the design process are not built into traditional database systems. Such capabilities might include search for components/assemblies that satisfy required functions, explicit representation of physical and functional decompositions and the mappings between them, simulation of behavior and performance, (partially) automated reasoning about a design, and more. Since design databases have not been designed specifically for these purposes, they are limited in their ability to meet needs for design of large-scale engineering systems.

The design repositories of the future would provide, in addition to catalog data, will also provide images, various information models (including knowledge structures, analysis and design theories,) application notes, and active models. For example, if we were to find out the behavior of a motor, i.e., speed vs torque characteristics, we could simulate it in the computer instead of physically conducting various experiments. Hence interface standards are required for representing form, function and behavior of artifacts.

6. Design Evolution Databases

Product Data Managers (PDMs) are normally used as design evolution databases. Object Management Group's (OMG) PDM Enablers specifications document, located at http://www.omg.org/arch2/mfg/98-02-02.pdf, provides various object models required to interface with commercial PDMs.

7. Illustrative coarse-grain use cases

In the following, we present highly abstract, coarse-grained use cases illustrating interactions between designers and other participants using the protocols described above and graphically illustrated in Figure 2. In order to provide a capsule abstract view, only actor-to-actor interactions are described, instead of interactions through the shared information bases. Further, the software reaction can only be described when each of the use cases shown is decomposed into its constituent sub-use cases. The term "design" means the computable representation of the design description, and not the (eventual) physical realization of that description.

Between traditional CAD systems. Designer A on CAD system X forwards the current state of a design to Designer B, operating on CAD system Y, for further development using expertise, history, knowledge, etc. available to Designer B only. Designer B receives Designer A's design, performs the necessary development steps, and returns the extended design to Designer A. Designer A receives Designer B's extensions, together with any comments, annotations and critiques provided by Designer B (i. e., there may be unanticipated, as well as the anticipated, results returned). The process may iterate to satisfy constraints or optimize design.

Between CAD systems and analysis packages. This is described in detail in the Design/Analysis Facilitation use case in the OMG RFI.
(URL: http://www.omg.org/homepages/mfg/mfgppe.htm#PPE RFI)

Between knowledge-based design systems and traditional CAD systems. Designer A, using a knowledge-based design system, performs a function-to-form transformation to synthesize a highly abstract design realization. Before any analyses (such as kinematic analysis) can be performed to establish the behavior of the design, a much more precise, but not necessarily more detailed, geometric representation of the form is needed. Designer A sends the abstract design to CAD Operator B, operating on a traditional CAD system, to create the necessary geometric description. The geometric model is returned to Designer A, who reviews it, accepts it and appends it to the current state of the design (it is an unsolved research question whether an abstract form description can be automatically extracted from the precise geometric representation). Again, cycles of iteration may be involved.

Between traditional CAD and immersive CAD systems. Designer A, operating on a traditional CAD system, has reached the point in the design process where the ergonomics of the design's interfaces has to be evaluated. The designer sends the design to an immersive CAD system, where Designer B simulates the design's behavior and collects performance data. Designer B's evaluation, collected data, and critiques, and related information, are returned to Designer A, who evaluates them and appends relevant data to the design description.

Solid interchange format. This is largely, but not exclusively a one-way interaction: the geometric representation from the CAD system is transferred to the layered manufacturing equipment in a manner analogous to NC (Numerical Control) machining information. Two-way interactions may occur if, for example, the slice thickness selected by either the designer or the process planner violates some constraints of the other participant.

Between various CAD systems and assembly planning systems. Designer A, using a knowledge-based design system, forwards a proposed design to Assembly Planner B, either directly or *via* a traditional CAD system, for evaluation of assembly implications. The assembly planner's tool returns trajectory, orientation, and sequencing data. If assembly conflicts are detected, they are communicated to the designer. If assemblability is established, the designer appends assembly process planning data to the design. Immersive CAD may be invoked to simulate the assembly process, which will aid in determining potential assembly conflicts and also provide various inaccessible zones. This information can further aid the assembly planning process.

Between CAD and process planning/manufacturing systems. Designer A forwards an early conceptual design to his counterpart Conceptual Process Planner, who generates a conceptual process plan and a cost estimate appropriate to the stage of the design process. After negotiation, with possible iterations, the design process moves forward. At a later stage, the designer has a more detailed preliminary design description and requests a manufacturability evaluation and/or a tolerance analysis. The results of the process planning and manufacturing software are returned to the designer. At still later stages, the designer's detailed design is submitted for detailed process planning and definitive costing. Interactions working in reverse are difficult to conceive at the present state of knowledge, e. g., an interaction intended to synthesize a conceptual design that utilizes or optimizes the available manufacturing processes and/or resources of an organization.

Interaction with design repositories. In the earliest stages of the design process, the designer browses the design repository for useful precedents, for competing designs, for available or preferred components, or even for "templates" of user and functional requirements of previous design projects. Design fragments retrieved from the repository and accepted by the designer become elements of the design *exactly as if* they had been generated from scratch by the designer, and may be modified or adapted to satisfy current constraints. At later stages of the design process, the designer deposits entire designs, or selected fragments, in the repository for potential future retrieval, adaptation and reuse. Still later in the lifecycle of the artifact, evaluation measures about manufacturability, usability, durability, etc., may be appended to the design in the depository to guide future retrievals and adaptations.

Appendix A: Current Research Activities at NIST

In this appendix, we provide brief summaries of several projects at NIST. These projects address the issues described in Sections 4 and 5. For each of these projects we discuss industry needs, our long term goals, and our objectives. Although the primary outcome is a set of interface specifications and representations, we hope that these specifications and representations will facilitate the development of interoperability standards.

A1: Short Term Parametrics

Problem/Opportunity: The CAD data exchange standard ISO 10303 (STEP) lacks the ability to transfer design intent in the form of parametrization and constraint data. This means that CAD models as currently transferred by STEP convey no information regarding what are and are not permissible modifications in the receiving system. The absence of this information makes it hard to edit models for the purpose of design optimization or in response to feedback from downstream processes such as manufacturing. Much time is wasted in industry in trying to reconstruct lost design intent information following current STEP model transfers. We have the opportunity to help in enhancing STEP so that design intent can be captured and exchanged.

Goal: The goal is to make US industry more efficient by providing an enhanced standard for CAD data exchange. This will save significant non-value-added CAD operator time that can be employed for more productive purposes.

Objectives: The objectives are to provide extensions to the STEP standard as it currently exists. Two different approaches need to be taken to cover the methods used internally by different CAD systems for the capture of design intent:

1. Approach 1 works by associating additional information with elements of the types of CAD models that STEP currently transfers. This requires the development of a new ISO 10303 Integrated Resource.

2. Approach 2 uses an entirely different method of representing CAD models, not currently used by STEP, but permitting much greater representational power for the future. In this approach a model is represented in terms of the sequence of constructional operations used to build it rather than, as at present, the end result of that process. New ISO 10303 resources for this purpose cannot be built upon existing resources in the standard, since no suitable ones exist.

The ISO TC184/SC4 Parametrics Group, led by one of group members, is tackling the development of the required new resources for both approaches. Progress is measurable against the ISO document development process. New parts of the STEP standard have to go through the phases Preliminary Work Item (PWI), New Work Item (NWI), Working Draft (WD), Committee Draft (CD) and Draft International Standard (DIS) before reaching the International Standard (IS) status.

Approach 1 is now at the NWI stage, and a complete Working Draft of the new resource is almost complete. It is intended to have a Committee Draft ready for the ISO voting process before the end of 1999. The aim is to progress this resource to IS status before the end of 2001. Approach 2 is at the PWI stage. The requirements analysis is complete, and decisions are now being taken on the best way to formulate the new resource documents. The aim here is IS status by the end of 2002.

A2: Open Assembly Design Environment

Problem/Opportunity: The Open Assembly Design Environment project seeks to capitalize on advances in communication and computational technologies to expand the Design for Assembly process model to encompass the complete product realization process.

Goal: The goals of the project are to identify representations and issues for the next generation of assembly-related standards and to assist designers with assembly considerations throughout the phases of a product’s design—from conception to final process plan development.

Objectives: The objectives of the project are as follows: 1) Develop an assembly-oriented representation that supports collaborative design and uses standardized interfaces to integrate assembly-oriented tools with existing and emerging CAD applications; 2) Identify and address issues that could accelerate the use of assembly-oriented tools in early stages of design; 3) Identify assembly representations and integration issues that aid in standards development by the design community; and 4) Illustrate a solution to the identified issues by developing a demonstration virtual assembly tool that augments existing CAD systems with a virtual reality subsystem.

A3: Traditional CAD to Immersive CAD Interfaces and Standards

Problem/Opportunity: Immersive CAD systems can be viewed as a natural extension or enhancement to current computer-aided engineering (CAE) systems, yet very different methods are used to visualize and manipulate the underlying product model. This results in a separation of data between the immersive CAD systems and that of the traditional CAD systems. The evolution of modern CAD systems toward integration with immersive visualization systems is driving the need for standardized interfaces and representations to enable system interoperability.

Goal: The goal of the project is to develop the appropriate interfaces and standards that will be used by industry for the integration and interoperability of traditional and immersive CAD systems.

Objectives: The objectives of the project are as follows:1) Develop the appropriate application and user interfaces for a prototype system; 2) Integrate several CAD systems with the immersive environment in a prototype system; 3) Provide input into the development of appropriate interfaces and standards for interoperability of traditional and immersive CAD applications; and 4) Work with industry to assess their integration needs and to drive the standards development.

A 5: Design for Tolerancing of Electro-mechanical Assemblies

Problem/Opportunity: Tolerance design is the process of deriving a description of geometric tolerance specification for a product from a set of specifications on the desired properties (performance) of the electro-mechanical assemblies. Existing approaches require detailed knowledge of geometry of assemblies and are mostly applicable during the advanced stages of design, leading to a less than optimal design process. Significant gains can be achieved by effectively using evolving assembly and tolerance information to influence the design of an assembly. In order to carry out early tolerance synthesis and analysis in the conceptual stages of the product design, we need to devise techniques for representing function-behavior-assembly models that allow the tolerance analysis and synthesis, even with the incomplete data set. The overall goal is to help US industries to profoundly improve the quality and reduce the cost of electro-mechanical assemblies and better comply with standards.

Goal: Motivated by this, we aim to identify and explore the following goals for future research that we believe can enhance the scope of tolerancing to the entire design process. The first goal is to advance tolerancing decisions to the earliest possible stages of design. The second goal addresses the appropriate synergistic use of available methods and best practices for tolerance analysis and synthesis, at successive stages of design. Pursuit of these goals will lead to a definition of a multi-level approach called design for tolerancing (DFT) that will enable tolerancing to be addressed for the entire design life. Finally we intend to develop the integrated, comprehensive, and neutral object architecture for function-assembly-behavior model.

Objectives: The objectives of this project are as follows: 1) Provide input into the development of tolerance standards; 2) Develop representations for encoding tolerance information throughout the design life cycle; and 3) Develop an object-oriented architecture for integrated and comprehensive function-Assembly-behavior (FAB) model.

A6: Knowledge-Based Systems Interoperability

Problem/Opportunity: Recent reports by Forrester Research[2] indicate that 40% of information technology budgets ($82 billion in 1998) is spent on application integration. In a manufacturing sector example, according to a 1999 Research Triangle Institute report[3], imperfect interoperability imposes at least $1 billion annually on the members of the US automotive supply chain. Beyond that, the National Research Council[4] has identified a major research challenge in embedding knowledge into design and manufacturing applications. Efforts such as STEP have focused on standardizing the exchange of data; however, few efforts have revealed attempts to describe more abstract, knowledge-intensive engineering information. As a result of the confluence of these events, there is both a problem in developing and an opportunity to develop testable knowledge exchange mechanisms (KEMs), where agents - both human and computer - can exchange specific design and manufacturing knowledge in a meaningful way.

Goal: The goal of this project is to develop an initial specification for the interoperability of knowledge-based systems (KBS) with each other and with traditional computer-aided design (CAD) systems.

Objectives: The main objectives of this project, and their associated deliverables and time frames, are as follows: 1) Perform a requirements analysis for exchanging information; 2) Develop metrics to evaluate and assess KBS tools and; 3) Propose a format for exchanging information between KB systems and KBS and CAD; 4) Investigate available representation scheme formalisms, and develop new ones, if necessary, required for communicating design and manufacturing; 5) Develop sample models of design representations in different computing environments; 6) Develop metrics to evaluate the performance of systems interoperating; and 7) Build consensus and transfer technology.

A7: Solid Interchange Format

Problem/Opportunity: Rapid Prototyping (RP) is emerging as an important manufacturing technology. The current data interface to most commercial RP systems is through the STL (stereolithography) *de facto* industry standard data format. There are several disadvantages of the STL format, including redundant data within the file, little product intelligence (e.g., no knowledge of geometrical features, part surfaces, or topology), large file size for complex parts, no accommodation for multiple materials, colors, or material properties, no mechanism to apply tighter tolerances at critical part features, and lack of a true geometrical part representation. Hence, there is a need for a new CAD-RP interchange format that addresses above issues.

Goal: The goal of this project is to improve current data transfer capabilities from computer-aided design (CAD) systems to rapid prototyping (RP) systems through development of a proposed alternative to the existing CAD-RP interface.

Objectives: . 1) Define the requirements, content, and structure for the proposed alternative RP data transfer mechanism (currently referred to as the Solid Interchange Format or SIF)

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[2] See, for example, http://www.openapplications.org/interop/index.html.

[3] Brunnermeier, SB, SA Martin, "Interoperability Cost Analysis of the US Automotive Supply Chain," RTI Project Number 7007-03, Research Triangle Park, NC, March 1999.

[4] "Information Technology for Manufacturing: A Research Agenda," National Research Council, Washington, DC 1995.

to accommodate current data exchange needs and to enable more advanced capabilities from next-generation manufacturing systems. 2) Analyze existing manufacturing data standards, including the STEP (ISO 10303) international standard for representation of product model data, to assess possible suitability and/or applicability to RP data transfer. 3) Coordinate interaction among related SIF development efforts and facilitate possible new standards for the RP industry.

A8: Design and Process Planning Integration (DPPI) Project

Problem/Opportunity: In current industrial practice, conceptual design, process/resource selection, time/cost estimation, detailed design, and process planning are performed independently, without integrated software tools. This is primarily because conceptual design systems, detailed design systems, cost estimating systems, and process planning systems are not designed for interoperability. Design and manufacturing data and messages cannot be efficiently sent from one system to another. Due to this information barrier between design and manufacturing systems, errors made during the early stages of design cannot be timely discovered and 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. Hence, there is a need for developing an infrastructure and associated protocols for integrating design and manufacturing information throughout the design-manufacturing life cycle.

Goal: The long-term goal is to develop systems interface specifications for integrating design and manufacturing throughout the entire product development cycle. The short-term goal is to develop specifications and prototype systems to enable manufacturability analysis in conceptual product design.

Objectives: The objectives of this project are as follows: 1) Define industry needs and survey the current state of art and practice; 2) Analyze requirements and define the concepts inherent to the design and process planning interface specifications and prototype development; 3) Develop information models and protocols and validate them using the advanced design and process planning systems; 4) Build consensus among major U.S. manufacturing companies; and 5) Transfer the technology for commercialization and initiate standards activities.

A9: The NIST Design Repository Project

Problem/Opportunity: While advances in the area the area of Internet computing have improved the means for sharing and exchanging information, the more significant barrier to product development is not the problem of providing distributed access to distributed information, but of finding the information that’s needed. The need for rapid retrieval and subsequent reuse of knowledge, driven by pressure to reduce product development times in industry, has resulted in an increased focus on methods for representing and storing engineering artifact knowledge. Traditional design databases, which merely provide access to schematics, computer-aided design (CAD) models, and documentation, are inadequate for this purpose. The emerging research area of design repositories is aimed at addressing these industry needs.

Goal: The overall goal of this project is to develop an information modeling framework to support the creation of design repositories, the next generation of design database. This project is driven by industry needs for technology to support the increasing role of knowledge-based design, including the representation, capture, sharing, and reuse of corporate design knowledge. The outcome of this work will be the implementation of a prototype design repository tool suite that addresses the objectives laid out below. This tool suite will consist of web-based interfaces, a client/server-based architecture, and example design repositories to demonstrate the functionality and utility of the design repository concept.

Objectives: The main areas of work within this project are as follows: 1) Develop information models for the representation of design artifact information; 2) Design interfaces for creation, editing and navigation of design artifact repositories; and 3) Organize certain types of engineering knowledge into taxonomies. Specific technical milestones include the development of information models for design artifact knowledge and the mapping of these models into the Extensible Markup Language (XML), the development of taxonomies of engineering function, associated flows, and other types of classification schemes, and the implementation of a client/server-based architecture that uses XML and Java at the server side and HTML and Javascript at the client side, and the development of example design repositories.

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