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Process-Based Quality (PBQ) Tools Development

Federal Manufacturing & Technologies

J. L. Cummins

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PROCESS-BASED QUALITY (PBQ) TOOLS DEVELOPMENT

J. L. Cummins

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Topical Report

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Abstract

The objective of this effort is to benchmark the development of process-based quality tools for application in CAD (computer-aided design) model-based applications. The processes of interest are design, manufacturing, and quality process applications. A study was commissioned addressing the impact, current technologies, and known problem areas in application of 3D MCAD (3-dimensional mechanical computer-aided design) models and model integrity on downstream manufacturing and quality processes. The downstream manufacturing and product quality processes are profoundly influenced and dependent on model quality and modeling process integrity. Our goal is to illustrate and expedite the modeling and downstream model-based technologies for available or conceptual methods and tools to achieve maximum economic advantage and advance process-based quality concepts.

Summary

This effort is a summary of results of benchmarking 3D model-based design, manufacturing, and quality process applications. Particular tools in use to implement process standardization and control site-specific

processing uniformity were targeted for illumination, examination, and study. Additional progress is being achieved almost daily, and updated reporting is considered beyond the scope of this effort.

Benchmarking efforts for processes were largely restricted to commercially reported studies and media reports as a result of restricted travel funding. Such studies are included as reference material in appendices.

MCAD (mechanical computer-aided design) model design for manufacturing was studied to assess the present progress achieved in heavily computer-oriented business endeavors. While many examples of cost-effective applications have been developed, when compared to prior (pre-CAD, including 2D CAD) drafting and design practices, much more robust and disciplined 3D solid model design processes are being recognized as desirable maturing requirements. More than just "pretty modeling illustrations" are required for the downstream processes of manufacturing and quality production. To maximize the benefits of model-based engineering, a more broad understanding of the applications intended of the model as downstream production tasks are performed must be imposed in the earliest model design phases. This effort is intended to examine, illustrate, and present commercially available concepts, practices, software, and hardware tools to aid in raising the quality and efficiency levels of model-based product manufacturing and acceptance processes.

3D MCAD modeling provides a more intuitive product design approach. The model can provide better control and tracking of product features, detailed volumetric data, and control of product feature compatibility with assembly interfaces. Some known and/or newly revealed problem areas in modeling applications are in translation errors, buried model features, product data system interfacing, design model quality certification, configuration management, and model archiving. Today model quality can be assessed with independent model element standardization software, geometry checking modules, and model certification/configuration management processes. More maturity in quality modeling processes will be evolving as standardization tools are routinely applied.

Downstream manufacturing processes are dependent on model quality. Numerical control (NC) programming may require creation of multiple in-process models that are generated from the product design model, but illustrate the sequences of feature generation or the decomposition from initial stock form into processed features. Throughout the creation and application of in-process models, the adherence to the product model designer’s intent must not be compromised. A major aid is sometimes found in rapid stereolithography prototype generation for mock-ups that both confirm and validate the design intent or visualize undesirable constraints not previously recognized. Early design corrections are much less expensive than those found later in the initial production cycle.

Quality processing begins with the model creation. The robust quality methods used to standardize model creation define the fundamental attributes that the model carries downstream. The robust quality methods applied in creating manufacturing process programs, documentation, and instructions are fundamental attributes defining process-based conformance to requirements. And quality methods applied to acceptance evaluations to achieve final requirement validation are inherently linked to the manufacturing process. Quality must be "processed in"; it can not be "inspected into" a product. That fact is the fundamental concept leading to process-based quality. There is no other base for product quality.

The methods and tools that are essential to model-based manufacturing require a more broad-based level of integrated understanding and attention to detail for all associates involved in order to effectively apply process-based quality technology. This project proposes to aid in the evaluation, development, and understanding of methods and tools to this end.

Discussion

Why was this project undertaken?

Changes within the Nuclear Weapon Complex (NWC) production environment are being driven by emerging design concepts that utilize 3-dimensional computer-aided design (3D CAD) models as the product definition in place of the traditional 2D paper-based drawing product definition systems of the past. Past procedures must be modified to accommodate the different administrative and engineering processing methods based on 3D model product definitions. We are entering a new era that demands that we not just adapt, but that we *lead* the way to improving how we operate internally and how our design agency customers do business with us.

The economies inherent in model applications are imperative in the downsized NWC. We *must* develop engineering, manufacturing, administrative, and quality processes that produce products cheaper, faster, and of equal or better quality with reduced consumption of resources.

A shift from product-based to process-based acceptance requires definition of tools, methods, and techniques to guide processes toward increased excellence.

Internal site-specific business practices need to evolve to apply process-based quality tools. This project proposes to aid in the evaluation, development, and understanding of methods and tools to this end.

Scope and Purpose

The nature of this development effort shall assess the present status of design, manufacturing, and quality processes as engineering applications of 3D models expand. Future guidance in shaping processes and tools to capitalize on the increased tempo of process engineering tasks and inspection planning preparations shall be addressed.

Methods used to achieve objectives are illustrated in detail in appendices that contain industry-leveraged benchmarking studies and reports. The appendices accomplish in summary form those benchmarking efforts that were restricted by travel budget constraints and various company proprietary concerns. The primary objective is visibility of development and implementation of COTS (commercial-off-the-shelf) quality processing tools including techniques, software, and best practices.

Today's NWC environment budgetary restrictions require*doing more with less.* Where technology permits improvement in process planning by working directly with a qualified 3D model instead of re-creating process illustrations, etc., those economies are welcomed. Efficiencies are increased.

Objectives to be obtained and/or enhanced are site-to-site collaboration on lessons learned and tools applied, reductions in time required to plan processes, direct assessment of model design features early in the process, and control and communication of model-based interface details.

Manufacturing process improvement techniques and tools applied through application of 3D models include reduction or elimination of acceptance flow time and expansion of process audit approaches to product acceptance where this more cost-effective concept can be proven. Similar efforts and experience sharing within the NWC are progressing.

Prior Work

Previous work reported on an effort to integrate final inspection elements into up-front processes that generate quality conformance. This process-based quality concept is a modernized extension of that approach with an updated view of the advances made in 3D modeling technology.

Six Sigma teams evolved process characterization and control concepts widely applicable to all business processes. Improvements are continuing. Primarily manufacturing processes have traditionally received fundamental attention, as they will here; but Six Sigma methods are also appropriate for processes as diverse as procurement, warehousing, information management, and administrative tasks. Such processes are classified as administrative, service, or transactional processes and may transparently consume large portions of an enterprise resource.

Activity

Initial activities centered around the industrial liaison routinely conducted with efforts by the National Institute of Standards and Technology (NIST) and with general industrial practices to assess 3D model application technology. A cooperative R&D (research and development) study was commissioned to assess the impact of 3D MCAD (3-dimensional mechanical computer-aided design) model integrity on downstream manufacturing and quality processes. (Reference Appendix A.) An industrial benchmarking report, *3-D MCAD Model Integrity Impact on Downstream Manufacturing and Quality Processes*,[1] provides a pertinent review of the status of modeling techniques and practices and the resulting problem areas CAD software vendors and standards groups are presently working to improve.

NIST First Part Correct Workshop, A Continuing Industrial Liaison Activity

More than 50 attendees from 43 diverse organizations participated in the First Part Correct (FPC) Workshop. FPC may be generally defined as "the ability to transition from design concept to a finished product with absolute certainty of a correctly produced part or product." The workshop was held at, and hosted by, NIST in April 2000.

First Part Correct Workshop participants may be identified organizationally through the following major divisions (see Table 1).

Table 1. First Part Correct Workshop - Major Divisions of Participants

Consortia:	IMTI (Integrated Manufacturing & Technology Initiative)
	CAM-I (Consortium for Advanced Manufacturing – International)
	NCMS (National Center for Manufacturing Sciences)
Industry Sectors:	Ford
	GM
	Northrop Grumman
	Procter & Gamble
	Honeywell Federal Manufacturing & Technologies (FM&T)
Academia:	Penn State
	University of Southern California
National Laboratories:	LLNL (Lawrence Livermore National Laboratory)
	SNL (Sandia National Laboratory)
Government Agencies:	NIST (National Institute for Standards and Technology)
	NASA (North American Space Agency)
	DOD (Department Of Defense)

The FPC workshop was structured, well facilitated, and had information gathering instruments in place at the start. The FPC workshop was conducted in order to identify critical topics that may require further study as candidates for cooperative R&D activities.

Understanding Benchmarking[2]

Benchmarking is not industrial tourism.

Benchmarking:

1. Represents a tool for the identification of best practices.
2. Is an effective TQM (Total Quality Management) approach for guiding improvement.
3. Is a formalized way to manage change.
4. Helps determine the most important things to improve.
5. Helps determine the best approach to use.
6. Establishes best practices.
7. Is not a magical solution to problems.
8. Is not a one-time program that's used and then forgotten.
9. Is not a single-person activity that can be done alone.
10. Is not competitive intelligence or market research.

Benchmarking is not operating in a "doing business as usual" manner. No matter how big a lead a company has today, doing business as usual can result in a future business decline. Benchmarking is not a task that is delegated to others. It requires commitment and involvement in all phases. It is a "way" of doing business. It is a key part of breakthrough strategy.

Benchmarking Concept Versus Process

Benchmarking is simple as a concept but much more involved as a process. The ultimate payoff is that you can become the best of what you do, and continuously improve on that superiority.

Benchmarking is a means of identifying best practices and using this knowledge to continuously improve our products, services, and systems so that we increase our capability to provide total customer satisfaction.

Benchmarking ensures that best practices from competitors or best-in-class companies will be identified. These in turn will point the way to needed improvements. Benchmarking can help locate new techniques and technologies that are used by best-in-class companies, whether they are competitors or non-competitors.

Benchmarking will help a company to realize the value of having a market focus rather than strictly an internal one.

Benchmarking is a continuous process of measuring products, services, and practices against the toughest competitors and/or those companies renowned as the leaders.

Benchmarking is a process used to identify, establish, and achieve standards of excellence, standards based on the realities of the marketplace. It is a process to be used to manage on a continuous basis.

Benchmarking draws upon the integration of competitive information, practices, and performance into the decision-making and communication functions at all levels of the business.

Benchmarking the 3D Model Design and Related Drafting Processes

Benchmarking the 3D model design and related drafting processes has made visible numerous poor design practices that are found even in high technology aerospace and electronics companies. Engineering drawings in an example case were found to exhibit an overall quality of only 3.64 sigma when the desired target was six sigma.[2]

A study by Prescient Technologies, Inc., presented case study data, as shown in Table 2.[3]

Table 2. Case Study Data - Product Model Designs

	Raw Data	Sigma
Number of Models Analyzed	1,562	
Number of Features / Model	21	
Total Number of Features Analyzed		
Number of Operations / Feature	14	
Total Number of Operations	461,776	
Number of Models "Passed"	544	
% of Models "Passed"	35%	
[illegible]	[illegible]	[illegible]

Defective Models (ppm)	651,729	1.1
Number of Features "Passed"	28,850	
% Features "Passed"	87%	
Defective Features (ppm)	125,333	2.5
Number of Operations "Passed"	428,680	
% of Operations "Passed"	93%	
Defective Operations (ppm)	71,671	2.8

3Used by permission. G. A. Finn,*Implementing Six Sigma in Engineering Design*, White Paper by Prescient Technologies, Inc., 245 Summer Street, Boston, MA 02210 (www.prescienttech.com), May 1999, p.17.

(Now http://www.planetcad.com/ PlanetCAD, Inc., 2520 55th Street, Boulder, CO 80301).

A set of data is presented here, as a result of a production analysis of a design process, using the Prescient Technologies DesignQA® design quality system. The study was conducted over a set of 1,562 design models, with a total of 32,984 individual part/feature quality assessments having been conducted (an average of 21.1 discrete feature or attribute analyses per model).

At a gross level, a non-statistical analysis yielded the result that 65% of the models failed the minimum quality assessment for release-to-manufacture. This translates into less than a 1σ process for models. The operations defect data translates to a defect rate of 72,000 parts per million (just under a 3σ process).

Obviously, to reach six sigma model quality levels, there is need for significant improvement in the standardization of design processes and model quality analysis. Tools to help accomplish this standardization are becoming available and are coming to our aid.

Identifying Variances in the Design Model

In order to identify variances from the desired results in the product model, a design quality system (for example, Prescient software products DesignQA and/or GeometryQA) should be used to analyze the model and compare it (feature by feature) with enterprise or company pre-defined quality standards. Other functional alternative software tools are also appearing in the commercial (COTS) market. An example for mapping the six-sigma process steps for a hypothetical model design quality system is illustrated in Table 3.

Table 3. Mapping the Six Sigma Process Steps for Engineering Design Models

Process Step	Software Tool (Suggested Prescient Technologies Products)	Responsible Person	Action
Define	DesignQA / GeometryQA	Program Technical Lead; Design standards manager; CAD/CAM/CAE support manager, Product Realization Team (PRT)	Manager/standards administrator, Design Agency (PRT) identifies CTQs (Critical To Quality) features; Configuration Standards.
Measure	DesignQA / GeometryQA	Design Engineer Product Engineer Model Designer	User executes application within the CAD and/or PDM environment for a given model or set of models.
Analyze	DesignQA / GeometryQA	Design Engineer Product Engineer Model Designer	Application creates "results" report, prioritizing and quantifying the quality of each model analyzed. User interrogates model(s) for each identified issue.
Improve	DesignQA / GeometryQA	Design Engineer Product Engineer	User and application together apply corrective actions to improve the

		Model Designer	quality of individual models.
Control	(Compatible PDM Certification Programs –To be determined. MATRIX ONE applications are evolving) Drive QA (A Prescient Technologies product)	PDM Administrator; Product/Program Manager; Engineering and Manufacturing Executives	Institute quality standards around the PDM release process. Constantly monitors aggregate quality information and takes strategic corrective actions (training, best practices, etc.)

The process for establishing the quality criteria, feature characteristics critical to quality (CTQs), is accomplished through *configuration* of the quality standards in the design quality system (DesignQA and/or GeometryQA). Several configurations (quality standards) can be developed for different purposes, release processes, or programs. An example of the application of DesignQA is illustrated in Appendix B.

Once this configuration process has been concluded, the design engineering team uses the design quality system to perform the analysis, and to develop the metrics. The design engineering team has the capability to take automatic or manual action to improve the quality of the engineering product. An update quality "stamp" is inserted into the model by the assessment software (DesignQA) for future reference.

Prior to release into the Product Data Management (PDM) environment, a CAD environment compatible PDM certification program (to be determined--MATRIX ONE and similar applications are evolving) should examine the product models to determine their quality levels, and assess the viability of their release into the production environment. If the subject model has been assessed an acceptable (low) score, the release process can occur. If that model exhibits defects in conflict with the standards imposed, it can not be released until corrected. The design quality system envisioned would apply the same acceptance approach to models that we apply to inspection of manufactured product.

Benchmarking the 3D Model Relationship to Manufacturing Processes

This section provides descriptions of the uses of 3D MCAD models in downstream manufacturing and quality processes and reports numerous advantages and problems in using the subject models identified by survey respondents as reported in the Brightstar study.

Types of MCAD Models

Wire frame models are simple stick model representations of a solid **Surface models** represent true mathematical models of the surface of an object. The MCAD **solid model** design process matches the actual manufacturing process by subtracting or adding solid sections from an original structure.

Feature Control—Most solid modeling systems create a "history tree"—a step-by-step record of the creation of features in the part design process.

Volume and Mass—Solid models contain detailed volumetric data.

The one disadvantage of solid 3D models is that the current solid model software applications are not as sophisticated and capable of generating complex curves and surfaces as surface model applications are at this time. However, this is an area where CAD software vendors are improving their products.

Current Uses of MCAD Models in Manufacturing Processes

3D MCAD solid models facilitate the development and execution of rapid prototype processes such as stereolithography, selective laser sintering, fused deposition modeling, and rapid machining.

Predicted enhancement of current standards such as the STEP standard and the many application programs within STEP are expected to more adequately address file definitions, model features, and design procedures. The benefits of a universal product feature definition standard include the ability to improve the automation of MCAD/CAM (computer-aided manufacturing) processes and improved communication and collaboration capabilities between all participants in the product development process flow. At the present time, this communication and collaboration must occur by manual methods.

The functional design system assigns a unique identifier for each feature as it is created and added to the MCAD model design. This identifier provides the key required to associate features within the MCAD solid model, manufacturing/quality process plans, and NC programs so future design revisions can be accomplished with modifications of the portions of manufacturing plans and programs associated directly with the changed feature(s). Therefore, maintenance of downstream dependent manufacturing instructions could approach a more efficient and effective automated change incorporation scheme if such associativity could be implemented. Presently manual methods prevail.

Visibility gained through the earliest applications of models illustrated the need for standardization and has led to the STEP efforts. Proprietary CAD formats were preventing the translation into business partners' and/or vendors' applications, and compatibility of the desired scale for economic business methods was impaired. STEP has been designed for solid model representation. Application of STEP translations and compatibility are slowly gaining industrial acceptance.

Manual Process Planning

3D MCAD models used in the development of process planning of product production largely still require manual translations or recreation of subordinate "in-process" models. Traditionally these models are used to design any additional product features required for manufacturing such as location holes, tooling datums, or the initial stock configurations for fixturing. Feature tolerances may have to be somewhat different (tighter) on the in-process models to accommodate processing constraints that achieve finished feature quality. This can lead to the need to create additional "in-process" models that address the requirements for inspection processing and documentation of finished feature criteria.

NC programming tasks use 3D MCAD models as CAM applications to generate the tool path movements of NC programs. NC programmers typically work interactively with a CAM application by identifying product feature boundaries, processing sequences, cutting tools, and specifications so the CAM application can automatically generate the tool paths required to produce the feature.

Model Shape Ambiguities Encountered

Modeling software default accuracy settings, usually created for the convenience of speeding up the regeneration of model features, can cause strange ambiguities in the model that are not usually visible to designers unless special techniques are employed. Changing the accuracy setting to enhance the NC programming accuracy can sometimes cause undesired protrusions to become visible and greatly complicate the NC programming task. Software tools for detecting and correcting these phenomena are becoming available as COTS tools. Suggested application software for example evaluations are GeometryQA from Prescient Technologies, Inc, Boston, MA, and CAD/IQ from ITI (International TechneGroup, Inc., Milford, OH).

Translations of 3D MCAD models from original formats to the formats used by a CAE, CAM, or downstream manufacturing application often create errors in the translated 3D models. Integrated MCAD/CAM applications developed by a single vendor are inherently compatible, and the transfer of current version 3D MCAD model data between these applications typically results in perfect translations with no errors. However, 3D MCAD model data translation from an original format to another format may yield errors that include:

1. Appearance of unexpected features
2. Complete loss of feature data
3. Partial loss of feature data (especially tolerance data)

4. Misrepresentation of feature geometry.

The high number of original 3D MCAD model errors suggests that there is a need to develop MCAD procedure standards and guidelines. A mature corporate set of standards that address file definitions, other assembly part interfacing feature specifications, design configuration control, datum surfaces, coordinate systems, part axis, and feature creation routines is imperative.

Providing only the nominal specifications of features in solid MCAD models is inadequate direction for the manufacture and design conformance of products. Capability to specify metrology requirements in computer-aided design, engineering, manufacturing, process engineering, and analysis is still presently needed for interoperability enhancement.

A set of semi-automated software tools that aid in process planning from models has been developed and enhancements continue. Machining processes are being developed to use the verified feature tolerances of FBTol (Feature-Based Tolerancing, a software product developed at Federal Manufacturing & Technologies/Kansas City) in an automated process planning mode by a software tool named FBMach (Feature-Based Machining, a companion software product also developed at FM&T/KC).

Current Uses of MCAD Models in Quality Processes

Models become the working tools for developing CMM inspection programs off-line. Software such as SILMA/Cimstation can work directly from a geometric model to generate CMM probing plans and strategies. Probe configurations can be evaluated to ensure no crashes and effective minimized probe configuration changes throughout the inspection cycle. The result frees CMMs for actual product inspection use while generating pre-planned CMM programs off-line, thereby decreasing process flowtime.

If the production quantities are large enough to justify designing and building dedicated gages, such gages can be designed from the product model and represent the envelope criteria to be inspected from the product geometry. Such gages are usually "attribute" inspection tools and simplify pass/fail determinations in semi-automated applications. Parametric readout devices can be added to attribute gages if specific design criteria actual measurement data logging is required. If high-speed automated production lines are planned, many times the inspection gages are desired as workstations on such lines and the product inspection is performed at speeds that support the process flow without separate off-line CMM inspections. Large-scale high-speed automated automotive applications based on MCAD models come to mind. Modeling may simulate the entire production facility.

Tools that appear to be most desired in the application of inspection processes presently address the inspection data acquisition, management, reporting, and statistical analysis domain.

Accomplishments

A specific achievement accomplished is a clarified definition of "process-based quality." Quality must be "processed in"; it can not be "inspected into" a product. That fact is the fundamental concept leading to process-based quality. There is *no other base* for product quality. The goal is to refine manufacturing and administrative processes to become so robust that defectives are virtually impossible. In past endeavors, product final inspection was emphasized as the prime effort for quality achievement. Final inspection will still be pursued, but the modern systems realize that manufacturing processes either make or break product quality. So there is economic advantage in moving the emphasis further upstream to concentrate on the manufacturing process. Improving product quality must improve the quality of the core-generating processes.

Clarification of the definition of process-based quality has evolved. Techniques for designing processes that utilize the digital model to accelerate process planning, tool design, and NC production methods with robust quality at reduced cost are being sought and developed. Machining processes are being developed to use the verified feature tolerances of FBTol in an automated process planning mode by a software tool named FBMach. Stringent quality requirements placed on the CAD model are becoming visible and viable as teams realize downstream manufacturing and quality assurance processes are highly dependent on validated design attributes and consistent modeling techniques. Quality that is derived from such proven robust design and manufacturing processes defines and yields process-based quality. This approach is the major accomplishment this project has achieved. Progressive expansion of these and other similar tool applications are progressing.

The result of a concentrated effort to re-evaluate processing results and corresponding inspection planning has reduced or eliminated several inspection steps on mature product production. Techniques for control and reviewed visibility of process-based quality results have been developed and established for future applications. Examples of the data sheets outlining the review process are presented in Appendix D. The list of results and suggested example tools achieved thus far in this development effort are in Table 4.

Table 4. Suggested Example Tools

Application Area	i. ii. Input Object	• Process	Example Tool (Suggested for Specific Evaluation)
Model Integrity	MCAD Model	Product Design	DesignQA

Model Geometry	MCAD Model	Product Design	CAD/IQ
Tolerances	MCAD Model	Product Definition	FB/TOL
Feature Decomposition	MCAD Model	Product Definition	FB/Mach
Machinability	Machining In-Process Model(s)	Product Definition	FB/Mach
Create NC Program	Machining In-Process Model(s)	Machining Product Definition	Mastercam (Model Shop applications) Unigraphics (Production applications)
Create Inspection Program	Inspection In-Process Model(s)	CMM Programmed Product Definition	CimStation
Product Data Acquisition	Product Inspection Data	Product, Process Test Data/Failure Analysis	PPTD/FA (Being re-engineered at FM&T/KC – combines past unique systems PTD capabilities.)
Product Acceptance	MCAD Model As Product Definition	Acceptance Criteria Definition	(To be determined) MATRIX ONE (and similar applications are evolving.)

Future Work

Advanced model-based manufacturing processes are one example of the changing environment within the NWC. Continuing development of methods for progressive application of new related technology to improve cost-effective robust manufacturing processes is imperative. Model-based product acceptance processes represent major paradigm shifts and infrastructure changes that initially appear to defy established conventions. For instance, the product definition form is changing from traditional paper to that of an electronic model. Developments of the procedural steps and tools to institutionalize the expansion of this technology while maintaining and improving resultant quality are needed.

Institutionalizing a uniform model-based environment across the NWC requires collaboration, participation, and agreement from all NWC sites. Model-based design, manufacturing, and acceptance systems must interface with shareable enterprise level information management systems. Future downstream tools such as an inspection acceptance criteria retrieval system that interrogates the model and extracts the inspection requirements for generation of inspection instructions are becoming desirable. The expansion of capabilities that associate process models with the parent product definition should also become a future integration development effort.

With the product definition becoming an electronic model, effective methods of reliably archiving those product definitions also becomes imperative. This concept of archiving represents an infrastructure impact that must accommodate progressive changes in the hardware and software that is essential to effective retrieval of product definitions from archives in the future. Standardization efforts, such as the STEP format, are essential.

A CAD environment compatible PDM certification program (yet to be fully evolved) should examine product models to determine their quality levels and detailed acceptance criteria, and assess the viability of their release into the production environment. This is viewed as a prime area for future work.

References

1 *3-D MCAD Model Integrity Impact On Downstream Manufacturing And Quality Processes,* Brightstar Information Technology Group, Inc., Central Region Headquarters, 2515 McKinney Ave., LB-17, Dallas, TX 75201 (www.brightstar.com).

2 Mikel J. Harry, PhD, *The Vision Of Six Sigma: A Roadmap for Breakthrough*, Phoenix, AZ, Sigma Publishing Company, 1994, pp18.4 – 18.5, 28.10.

3 G. A. Finn, *Implementing Six Sigma in Engineering Design*, White Paper by Prescient Technologies, Inc., 245 Summer Street, Boston, MA 02210 (www.prescienttech.com), May 1999, p.17.

(Now http://www.planetcad.com/).

4 *ISO 10303, Product Data Representation and Exchange*, commonly referred to as the *Standard for the Exchange of Product Model Data, STEP*, International Standards Organization, NIST, 100 Bureau Drive, MS 2150, Gaithersburg, MD 20899-2150 (www.nist.gov); also see (www.iso.ch/).

Appendix A

3-D MCAD Model Integrity Impact On Downstream Manufacturing And Quality Processes[1]

1Used by permission. *3-D MCAD Model Integrity Impact On Downstream Manufacturing And Quality Processes,* Brightstar Information Technology Group, Inc., Central Region Headquarters, 2515 McKinney Ave., LB-17, Dallas, TX 75201 (www.brightstar.com).

A Final Report To:

AlliedSignal

AlliedSignal inc.

Regarding:

3-D MCAD MODEL INTEGRITY IMPACT ON DOWNSTREAM MANUFACTURING AND QUALITY PROCESSES

Prepared By:

BrightStar Information Technology Group, Inc.

September 15, 1999

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Figures and Tables

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I. EXECUTIVE SUMMARY

This report provides the findings and conclusions derived from a benchmark study of the impact of 3-D MCAD model integrity on downstream manufacturing and quality processes. The study was conducted, at the request of AlliedSignal, by senior consultants from BrightStar Information Technology Group, Inc.

This report is divided into several sections outlining

- Status of Current Technology and Standards
- Potential Emerging Technology and Standards
- Known Problems with 3-D MCAD models
- Recommendations for:
- STEP Standards
- Product Feature Definition
- Future 3-D MCAD Development

A. Project Background

In order to review the status of 3-D MCAD models, the project team interviewed both vendors and users to ascertain both the current technologies and known problems in this area. Appendix A lists the users from AlliedSignal, Lockheed Martin Energy Systems, and Rockwell Collins, Inc. who participated in the survey. Vendors, including Parametric Technologies and IBM/Catia, were also interviewed to understand not only the current status of the industry, but also potential future advancements. Finally industry research reports from Daratech and Jon Peddie Associates were acquired to provide general market growth statistics.

BrightStar would like to thank all those who participated in this study.

B. REPORT FINDINGS

Based on a review of the three types of 3-D MCAD models: Wire-frame, surface and solids; there was general consensus regarding the specific advantages of 3-D modeling.

- More intuitive resulting in a shorter learning curve
- Better control and tracking of product features
- Provides detailed volumetric data
- Better control of product feature compatibility

It was also recognized that a major disadvantage of 3-D modeling was the lack of sophistication of the technology for generating complex curves and shapes which resulted in model discrepancies. However the vendors are aware of this problem and believe that it will be eliminated in the near future.

Key uses of the 3-D MCAD model technology are:

- Rapid Prototyping including stereolithography, selective laser sintering, fused deposition modeling.
- Manual Process Planning assisted by better visualization of the product and better understanding of product feature compatibility.
- NC Programming, Manufacturing Tolerance Management, CMM Programming which can be improved by better understanding of dimensional relationships of features.

While there are significant advantages to using 3-D MCAD models, the developing technology still has specific problem areas including:

- Imperfect Original Models. A lack of guidelines and user training has resulted in incorrect usage of the technology resulting in geometry errors and topological errors.
- Accuracy Specifications: Specification of complex models can cause problems due to the modeling software inaccurately generating gaps, unwanted protrusions, etc.

- Translation Errors: Switching between different software packages or even different versions of the same package can introduce modeling errors and data loss.

As the technology improves and moves to a more cost-effective platform, it is generally believed that 3-D modeling will quickly gain acceptance over 2-D and the market will expand rapidly, especially at the low-end marketplace. Based on the industry research reports, it was apparent that there were specific vendors who will be key players in this market: Parametric Technologies, Dassault, IBM. In addition, Autodesk is a leader in the low-end desktop marketplace.

C. REPORT CONCLUSIONS

A key advancement in the use of 3-D MCAD models would be the development of standards. The standards would address file definitions, model features and design procedures. These standards would not only assist in the translation from one package to another, but would also assist users in the appropriate steps to generating a correct design model. Currently the STEP standard, administered by ISO and NIST, is gaining widespread acceptance and therefore would provide a solid foundation on which to generate a more comprehensive standard approach.

One deficiency of the STEP standard is the lack of comprehensive product feature definitions. In developing an industry-wide standard, it is recommended that STEP is provided with a universal, vendor-neutral standard for the definition of product features that is acceptable and applicable to all processes involved in the product development cycle. The benefits of a universal product feature definition standard include the ability to improve the automation of MCAD/CAM processes and improved communication and collaboration capabilities between all participants in the product development process flow.

A complete product development process is provided in Figure 8. In future scenarios, the MCAD will start with a standard file format and workspace template that is automatically loaded with information including part design intent information including part functions and specifications for interfacing with features of other parts. The designer would then typically selects a raw material shape from an inventory of materials, including include castings or forgings, maintained by the

purchasing department or, if necessary, from the inventories of approved vendors. When creating part features, the designer can select and configure a master feature object to quickly and more thoroughly define the specific individual feature. The system assigns a unique identifier for each feature as it is created and added to the MCAD model design. This provides the key required to associate features within the MCAD solid model, manufacturing/quality process plans and NC programs so future design revisions can be accomplished with modifications of the portions of manufacturing plans and programs associated directly with the changed feature(s).

II. PROJECT FINDINGS

This section provides a description of the key project findings.

State of Current Technology/ Standards

This section describes the benefits and current uses of 3-D MCAD (three dimensional mechanical computer-aided-design) models in downstream manufacturing and quality processes and the anticipated evolution of 3-D MCAD model utilization that is expected to be implemented in the near future. Descriptions of the three types of 3-D MCAD models: wire frame, surface and solid models are provided as well as the general advantages of the latest and most beneficial type - solid models. The presentation of 3-D MCAD model types is followed by discussions of the current uses of 3-D MCAD solid models arranged in the logical sequence of the product development process. In closing this report presents anticipated future enhancements to CAD/CAM (computer-aided-design/computer-aided-manufacturing) technology and the expected impact of these improvements.

1. Types of MCAD Models

3D MCAD systems define geometry in the following three basic ways:

- Wire frame models are simple stick model representations of a solid. Wire frame modelers provide a 3-D representation of the product design, but do not include all mathematical surface data. These models are not effective for producing 3D tool paths because insufficient information is available from the model data file.
- Surface models represent true mathematical models of the surface of an object. The object may be represented graphically as a wire frame structure, but unlike wire frame models, the entire continuous surface is defined with mathematics. Even though surface models are constructed of individual entities joined or linked together, it represents one complex surface. The important difference between a surface model and a wire frame model is that the surface model mathematically describes the entire surface, not just the points that form the wire grid.
- Solid models are fully enclosed models that have volume and are created using cubes, cylinders, cones, spheres or extrusions of shapes. Solid modelers have the ability to represent surfaces like surface modelers, but the difference is that solid

models also contain information about how the various surfaces meet. This enables the designer to use

Boolean operations, such as the addition or subtraction of volumes. This capability allows designers to add, subtract or intersect solids in a process that is similar to the manufacturing process used to produce the part.

Advantages of 3-D MCAD Solid Models

- More Intuitive—Manufacturing engineers and shop floor personnel conceptually visualize parts as the removal or build-up of raw materials in production process operations. The MCAD solid model design process matches the actual manufacturing process by subtracting or adding solid sections from an original structure. Consequently, 3-D MCAD models are much easier for manufacturing people to understand, than 2-D drawings, which require more analysis and are more prone to misinterpretation.
- Learning Curve—Since solid modeling capabilities are more intuitive for manufacturing personnel, beginners typically are able to create high-end 3D models without the extensive training and experience that is often required for good surface modeling.
- Feature Control—Most solid modeling systems create a "history tree"—a step-by-step record of the creation of features in the part design process. In the course of design development, designers may need to edit, re-order or remove steps to improve a product design. The history tree provides direct, integrated access to the design development sequence so the designer can easily track back to the appropriate design sequence point and make a specific change without having to recreate the model. A history tree also enables a designer to suppress certain features, removing them from the model temporarily. This is an advantage for the NC programmer who can use the CAD file history tree design to limit metal cutting operations to a limited sequence of product feature definitions. For example, an NC programmer can temporarily suspend hole feature definitions while programming the base area machining process without actually deleting the holes.
- Volume and Mass—Solid models contain detailed volumetric data. This allows users to perform accurate mass calculations, including volume, center of gravity and moments of inertia. This can be very beneficial in designing parts where volume is a key design criteria important, such as keeping a bottle's volume constant through design changes or converting a teaspoon to a tablespoon.
- Shelling—Solid modeling offers an easy approach to constructing parts with a wall thickness such as plastic containers for consumer products. Once the solid shape is created, the designer simply enters the desired thickness and the solid modeler removes the excess material. The program can automatically offset external or internal fillets as it blends the design faces to create a "watertight" solid model of the hollowed part.

Disadvantage of solid 3-D models

The one disadvantage of solid 3-D models is that the current solid model software applications are not as sophisticated and capable of generating complex curves and surfaces as surface model applications are at this time. The gap between solid model and surface model application capabilities is closing and this disadvantage will probably be eliminated in the near future.

2. 3-D MCAD Market

This section provides a high-level analysis of the 3-D Mechanical Computer-Aided Design/Computer-Aided Manufacturing, Computer-Aided Engineering (MCAD/CAM, CAE) marketplace including 1998 actual sales compared with 1999 forecast sales and the use of geometric modeler kernels used by the major MCAD/CAM, CAE vendors. This analysis identifies the major vendors in the MCAD/CAM, CAE marketplace and quantifies their 1999 forecast sales, expected growth, and market share. The geometric modeler kernels used by the major MCAD/CAM, CAE vendors are identified by vendor and major product line.

Mechanical CAD/CAM, CAE Market Analysis

From the results of a recent survey, Daratech, Inc. forecasts that the Mechanical CAD/CAM, CAE market will grow 16.7% to $6.2 billion in 1999 (the full report from Daratech is provided in the Appendix). As a leading market research and technology assessment firm specializing in CAD/CAM and CAE, Daratech projects that Dassault, Parametric, Unigraphics Solutions, Autodesk, and IBM will be the growth leaders in the 1999 world-wide CAD/CAM, CAE market. Figure 1 and Figure 2 present the Daratech 1999 forecast and 1998 actual sales for the CAD/CAM, CAE market as a whole and for the market leaders. The solid column provides revenue amounts for the CAD/CAM, CAE system developers, while the outlined columns represent costs and revenues for CAD/CAM, CAE resellers.

1999 Fcst.

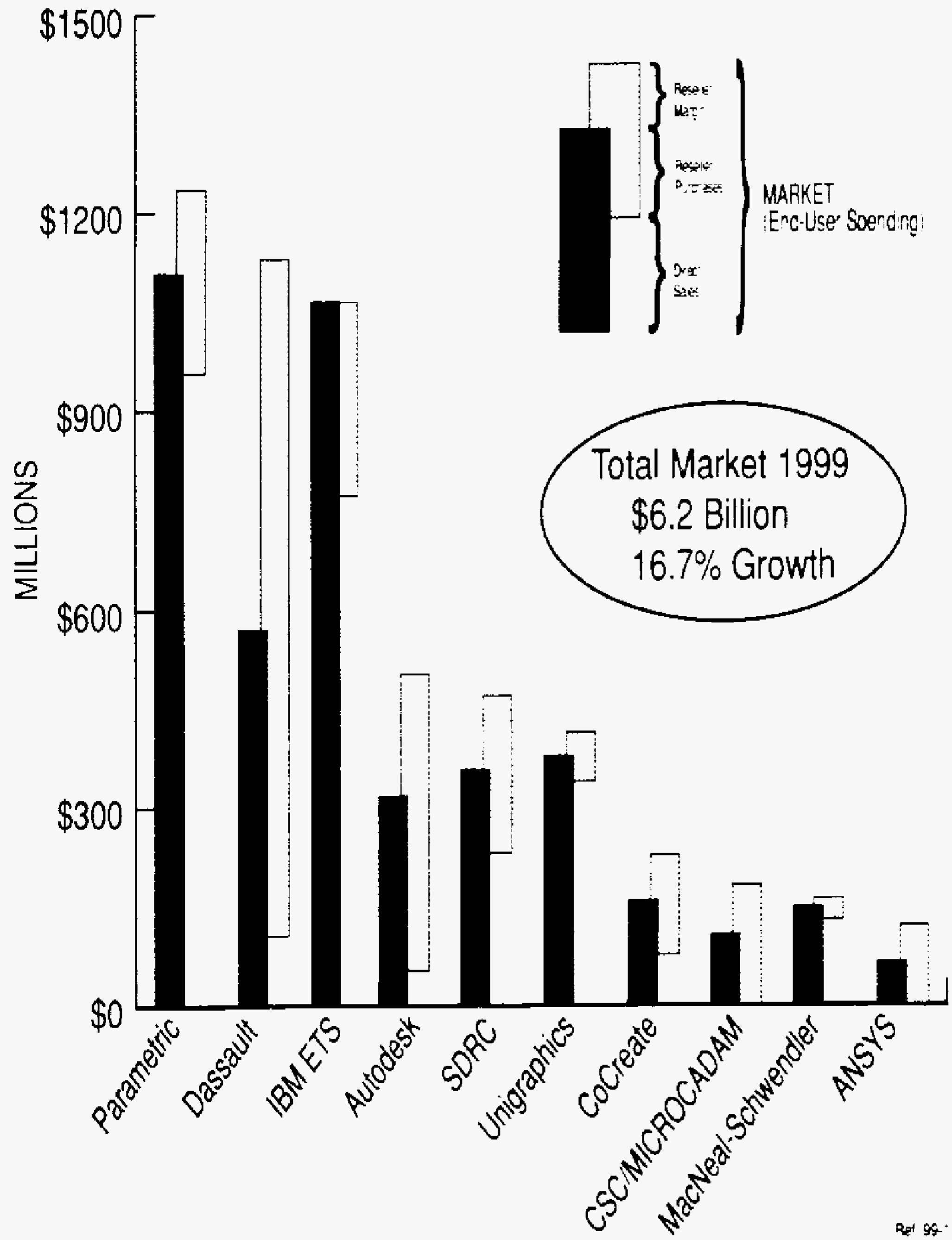
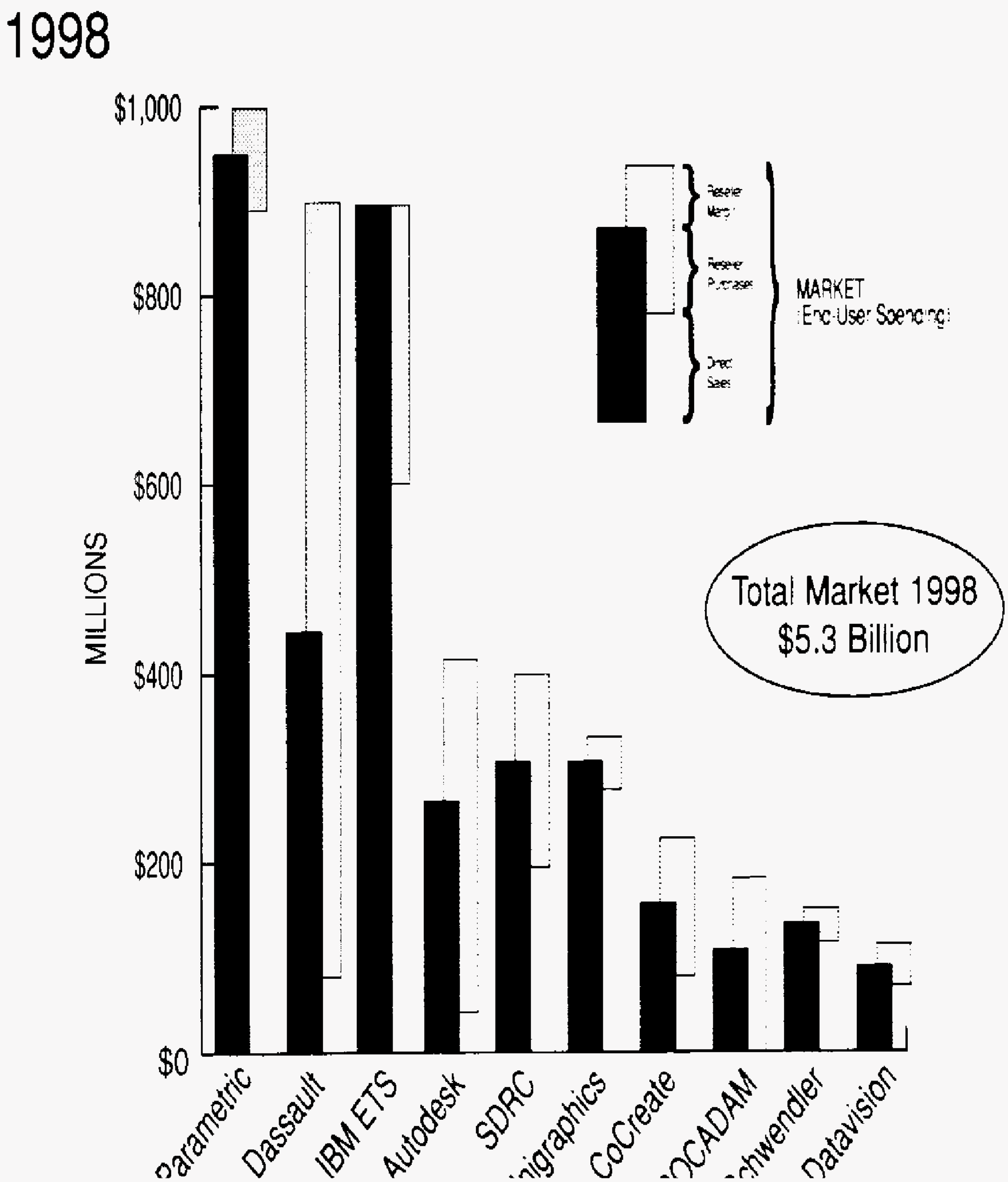

$1500
$1200
$900
$600
$300
$0
MILLIONS
MARKET
Total Market 1999
$6.2 Billion
16.7% Growth
Parametric
Dassault
IBM ETS
Autodesk
SDRC
Unigraphics
CoCreate
CSC/MICROCADAM
MacNeal-Schwendler
ANSYS

Figure 1 - 1999 MCAD/CAM, CAE Revenue Forecast



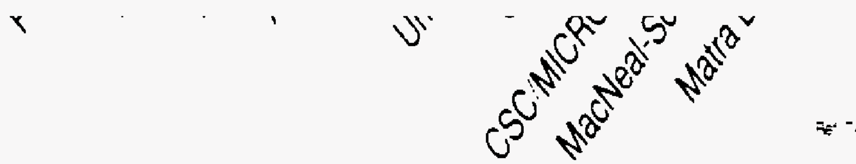
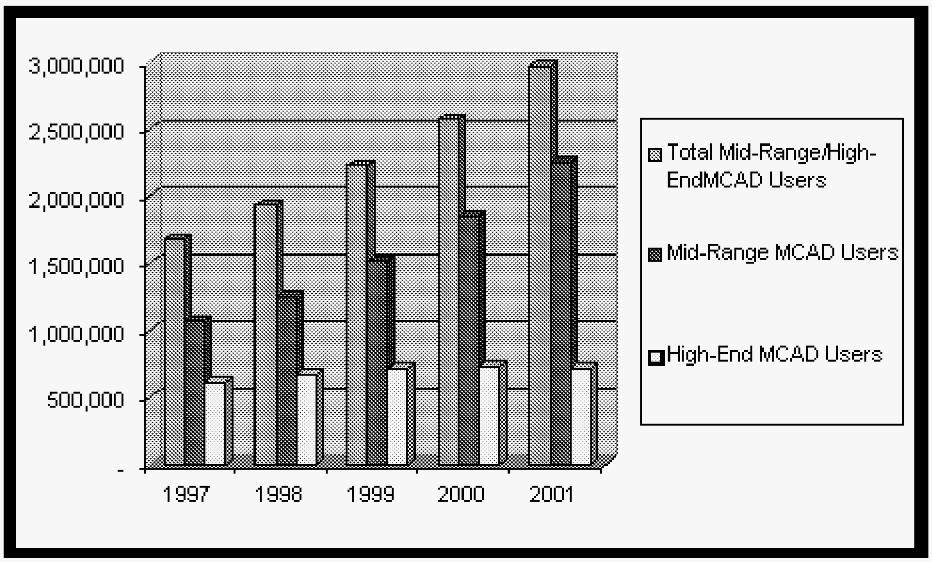


Figure 2 - 1998 MCAD/CAM, CAE Revenues

The MCAD market is often segmented into high end, mid-range, and low-end applications. Traditionally 3-D applications have been limited to high-end applications, but recently 3-D capabilities are migrating to mid-range applications such as Bentley MicroStation, Intergraph Solid Edge (now owned by EDS-Unigraphics), Autodesk Mechanical Desktop, and Solid Works (now owned by Dassault Systems). The projected growth of high-end and mid-range MCAD seats are displayed in Figure 3. The number of seats in the installed base of major high end MCAD applications is presented in Table 1, while the number of seats in the installed base of major mid-range MCAD applications is presented in Table 2.



Source: Jon Peddie Associates

Figure 3 - Mechanical MCAD User Base Projections

Table 1 - High-End Mechanical CAD Products for UNIX, Win NT

Company	Products	MCAD Installed Base
SDRC	I-DEAS, Artisan	146,925
Matra Datavision	Euclid Designer	140,000
Dassault Systems	Catia	106,000
Co-Create	Solid Designer	100,000
Computervision	Design Wave	97,000
Parametric	ProEngineer, PT/Modeler	93,500
EDS-Unigraphics	Unigraphics, UC/Creator	39,000

Source: Jon Peddie Associates 1998

Table 2 - Mid-Range Mechanical CAD Products for Win NT

Company	Product	Price	MCAD Installed Base
Autodesk	AutoCAD	3,750	500,000
Baystate Technology	CADKEY	1,195	290,000
Bentley	MicroStation	$ 5,3254	50,000
Autodesk	Mechanical Desktop	6,250	25,000
Solid Works	Solid Works	3,995	12,000
Intergraph	Solid Edge	5,995	7,500

Source: Jon Peddie Associates 1998

A key industry trend identified by Daratech is that engineering and manufacturing companies are increasing capital investments to reengineer new product development processes and to globalize product development processes in order to shrink product development time frames, significantlydecrease time to market, improve quality and heighten their global competitiveness. Daratech also cites that low-cost solid modelers are attracting more purchases, although revenue growth is subdued somewhat by lower-ticket solutions replacing some high-end application purchases. An analysis of revenue projections by Daratech for the 1999 MCAD/CAM, CAE market is provided in Table 3.

Table 3 - Analysis of 1999 MCAD/CAM, CAE Market Leaders

Vendor	Leading Applications	1999 Forecast Revenues	Annual Growth From 1998	Market Share
Dassault	CATIA, SolidWorks, Matra	$1.1 billion	26%	18.3%
Parametric Technology Corporation	Pro/ENGINEER, Pro/DESKTOP, Pro/MECHANICA Pro/ENGINEER 2000I	$1.2 billion	24.1%	20%
Unigraphics Solutions, Inc.	Unigraphics, Solid Edge, ProductVision, UG/WAVE	$412.2 million	22.6%	6.7%
Autodesk, Inc.	AutoCAD, AutoCAD 2000	$501.4 million	20%	8.1%
IBM Engineering Technology Solutions (excluding Catia)	MICROCADAM	$1.1 billion	19.3%	17.2%
SDRC (Structural Dynamics Research Corporation)	I-DEAS, Imageware	$469.1 million	16.6%	7.6%
Others		$1.42 billion		22.1%
Total		$6.2 billion	16.7%	100%

Geometric Modeler Kernels

The geometric modeler kernels used by major MCAD/CAM, CAE vendors are presented in Table 4. While Parasolid is the most popular geometric modeler kernel, there is no prevalent kernel used in the industry that could be used as the standard for 3-D MCAD model translations.

Table 4 - Geometric Modeler Kernels Used By Major MCAD/CAM, CAE Vendors

Vendor	Leading Applications	Kernel
Dassault	CATIA	Catia
	SolidWorks	Parasolid
Parametric Technology Corporation	Pro/ENGINEER, Pro/MECHANICA	PTC
	Pro/DESKTOP	Parasolid
Unigraphics Solutions, Inc.	Unigraphics, Solid Edge, ProductVision, UG/WAVE	Parasolid
Autodesk, Inc.	AutoCAD, AutoCAD 2000	ACIS
IBM Engineering Technology Solutions (excluding Catia)	MICROCADAM	Ricoh DESIGNBASE
SDRC (Structural Dynamics Research Corporation)	I-DEAS	SDRC
		IMAGEWARE

3. Current Uses of MCAD Models in Manufacturing and Quality Processes

This section provides descriptions of the uses of 3-D MCAD models in downstream manufacturing and quality processes.

Rapid Prototyping

The first manufacturing process in new product development is typically the production of a prototype of the design. Prototypes are often produced in different materials than the actual product design to facilitate rapid development of process automation programming and production of the prototype. 3-D MCAD solid models facilitate the development and execution of rapid prototype processes such as stereolithography, selective laser sintering, fused deposition modeling, and rapid machining.

Stereolithography, selective laser sintering, fused deposition modeling are rapid prototyping processes that build up a part adding material layer by layer using synthetic materials as opposed to the actual designed product material. These processes often use the Stereolithography Tessellation Language (STL) standard to convert MCAD solid model files directly into NC programs for building prototypes.

CAM (computer-aided-manufacturing) applications are now available to convert STL files directly into CNC tool paths for rapid machining prototype processes. Rapid machining prototype processes typically use softer materials than actual product materials to facilitate rapid production of the prototype model.

Manual Process Planning

3-D MCAD models are used in the development of process planning of product production. Traditionally these models are used to:

- Provide a visualization of the product to facilitate manual sequencing and definition of manufacturing process steps including the work center/equipment and task assignments for each process step,
- Design any additional product features required for manufacturing such as location holes,
- Develop the design of the interim part geometry resulting from each step of a multi-process production plan, and
- Prepare work instructions with detailed graphical views of involved features.

NC Programming

3-D MCAD models are used by CAM applications to generate the tool path movements of NC programs. NC programmers typically work interactively with a CAM application by identifying product feature boundaries and specification so the CAM application can automatically generate the tool paths required to produce the feature. The remaining components of the program such as tool selection, tool engagement motions, cutting speeds and feeds, step-over specifications, and tool retraction motions are specified manually by the NC programmer.

Further automation of NC programming is accomplished with the use of NC programming templates, which are predefined machining strategies incorporating all elements of the machining process required to create a predefined type of geometric feature. These templates are applied automatically to the specific geometry of applicable features defined by the 3-D MCAD model. This approach provides an object-oriented approach to NC programming that allows manufacturers to extend machining process optimizations to both existing and future NC programs with improvements to individual NC programming template objects.

Manufacturing Tolerance Management

3-D MCAD models are used to verify that manufacturing tolerances are correctly defined in the design phase and then fully adhered to throughout the manufacturing and assembly phases. This includes full 3D-tolerance stack-up analysis of components and assemblies to verify that designs and process plans will accomplish design objectives. Then 3-D MCAD models are used for the development of inspection plans for in process and CMM inspections of parts throughout the production process.

CMM Programming, Data Collection and Analysis

3-D MCAD models are used by CAM and computer-aided production engineering (CAPE) applications to develop coordinate measurement machine (CMM) programs that measure geometric parameters of machined parts and upload the data to applications that perform SPC analysis and record data. These applications generally take advantage of the 3-D MCAD solid model data structure to compute dimensional relationships between features and automate machine movements required to measure features. Typically, manufacturers develop CMM programs using DMIS (Dimensional Measuring Interface Standard) to generate programs in the neutral DMIS format that is accepted by most CMM control systems and is readable by non-technical personnel.

B. EMERGING TECHNOLOGIES/STANDARDS

This section describes emerging CADCAM technology enhancements that will improve the use of 3-D MCAD models in downstream manufacturing and quality processes.

1. Growth of MCAD Solid Models

Many CAM users are quickly shifting from wire frames to 3-D MCAD solid models due to increased use of solids within conceptual designs. The use of solids in CAM systems has grown rapidly with the emergence of affordable, mainstream solid modelers like SolidWorks, Solid Edge and Autodesk's Mechanical Desktop. One technological problem limiting 3-D MCAD solid models in CAM is that solid modeler applications are not yet completely capable of defining or generating complex shapes and surfaces. For this reason, some engineers still prefer to use surface modelers, wire frames, and 2D flat drawings. Another problem is that numerous manufacturers have significant libraries of legacy data, since the life cycle of a product may last up to five years or longer.

2. Associativity

"Associativity" is the linkage of a machining process to a part feature and is becoming an important concern for CAM applications. Instead of having to reconstruct process plans and NC programs in their entirety which each new product design engineering change, CAM applications are beginning to be able to identify the feature that was changed and modify only the machining process associated with producing the changed feature. This is a powerful capability that can significantly reduce manufacturing resource requirements, but is highly dependent on either using the native MCAD model file in the CAM process or accomplishing a perfect translation of MCAD models files that maintains the identity and integrity of design features.

3. Automated Process Planning and NC Programming

In a very recent development, the previously described NC programming template concept is being combined with 3-D MCAD solid models to implement two new technologies called Adaptive Feature Recognition (AFR) and Knowledge Based Machining (KBM). AFR identifies and associates part features with standard manufacturing features that can be produced with previously developed and verified machining strategies. KBM then assigns and programs the appropriate machining strategy to automatically generate process plans and NC programming to manufacture the part. It improves machining efficiency by comparing historically demonstrated machine tool process

capabilities with the tolerance requirements of the 3-D MCAD model. This enables the KBM process to select the best machines, operations and cutting tools to manufacture the part.

Future CAM programs fully incorporate AFR and KBM strategies to provide both expert- and experience-based process planning and CNC programming capabilities. "Out of the box," expert systems will provide a high degree of automation based upon extensive libraries of CAM techniques developed with input from experienced developers, machine tool manufacturers and user feedback. As an experience-based system, future CAM applications will allow users to store their own manufacturing techniques and statistically verified machining capabilities for specific machine tools, tooling packages, and feature based manufacturing processes.

4. Evolution of MCAD Data Transfer Standards

Connectivity is the ability to effectively exchange data between CAD and CAM applications. This is very important to CAM functionality because most product designs are developed with a CAD system and imported into the CAM application. Unfortunately, there is no prevalent interface standard, so CAM applications must be able to interface with numerous exchange platforms, including the neutral standards of IGES and STEP, the commercial standards of AutoCAD DXF and DWG, and solid modeling kernels such as the Parasolid-based XT and the ACIS-based SAT formats. These formats have been in competition for preeminence in the industry for the past three to five years, but have not been successful in establishing a clear-cut leader.

Many supporters consider IGES (Initial Graphic Exchange Specification), which has been in existence for 15 years or more, to be the industry standard. Though IGES receives much criticism because of its vagueness; it is still used by many manufacturers to translate data between CAD/CAM systems. STEP (Standard for Exchange of Product Model Data) is supported by the International Standards Organization) and has an advantage over IGES in that STEP has been designed for solid model representation. Many commercial platforms are also accepted as standards due to their popularity in the CAD/CAM marketplace. Parasolid (XT format) and ACIS (SAT format) are solid modeler kernels used by a significant percentage of CAD and CAM applications. Because the solid modeler kernel is integral to the solid model design, many CAM programs can read a native file directly from the CAD system if they both use the same kernel. It's easy and flawless because there is minimal translation involved in the data file transfer.

Of all data transfer approaches, the ability to read native files is the best solution, because it requires less effort, resources and time. The CAM application can simply read the file, recognize the features, apply machining processes, generate the program and make the part. When the part design is revised, the CAM application can recognize the feature associated with the revision and modify only the portion of the process plan and NC programs affected by the design change.

5. Application Integration

Application integration allows different software systems to work together for a single user. This can be accomplished by implementing the different functions physically in the same computer program or it can be performed with OLE (object linking and embedding) technology, which allows different computer programs to work together in one user interface view appearing seamless to the user. A specialized standard called OLE for D & M (for design and manufacturing) allows a CAM application to directly "ask" a CAD system for model data without the hassles of saving and opening files, or the technical problems of file translations. OLE application integration offers users the highly desired ability to acquire and integrate "Best-of-breed" applications in their CAD/CAM operations to reduce costs, improve quality, and cut product development cycle time in the pursuit of market leadership.

6. Web Enabling Technologies

The impact of Internet web technology on MCAD/CAM processes is and will be realized by speeding the delivery of designs, offering opportunities for collaboration, and providing web-based libraries of best machining practices. Already the Internet has reduced the time required to deliver MCAD models across large geographical distances from hours/days to minutes by replacing overnight/U.S Mail deliveries with

FTP (file transfer protocol) or email transfers. This capability has greatly reduced product development process cycles. In addition, web-based collaboration applications are emerging to provide an interface for manufacturing and design engineers to review the manufacturability of MCAD designs and alternatives for reducing manufacturing costs. Finally,

the Internet will provide an opportunity for machine tool and CAM vendors to build libraries of best practice machining routines for downloading by customers to optimize the use of the vendor's products or for nominal service fees.

7. CAM Production of Parts

Technologies such as stereolithography and metal laser sintering used traditionally to produce prototype models of products are now being considered to manufacture actual products and tooling. Following the rapid development of materials such as polyamides with glass additives, manufacturers are finding that stereolithography processes can produce parts that are resilient, practically unbreakable with relatively smooth surfaces. Furthermore, metal laser sintering processes can now produce metal inserts made of steel granulates for injection molds that require only secondary smoothing and polishing operations to be suitable for large production run operations.

C. REPORTED PROBLEM AREAS

This section reports problems in using 3-D MCAD models in downstream manufacturing and quality processes identified by the survey respondents.

1. MCAD Models

Survey respondents reported that 3-D MCAD models often had errors resulting from problems such as incorrect CAD procedures, accuracy specifications and incompatibility in the sequencing of MCAD design feature creation versus manufacturing processing requirements. This section describes problems found in 3-D MCAD models and the causes of these errors.

Imperfect Original MCAD Models

The lack of CAD design guides and insufficient CAD application training results in the improper use of CAD procedures. Our survey respondents reported frequent cases of incorrect usage of CAD procedures causing 3-D MCAD errors. One reported example of a CAD procedure error that created an unwanted sliver face was the use of a cut-through command by a CAD designer rather than the cut-to command to remove a section from a feature.

The survey respondents reported finding the following types of errors in original 3-D MCAD models:

Geometry Errors

- Gaps between faces and the edges of surface intersections (Figure 4)

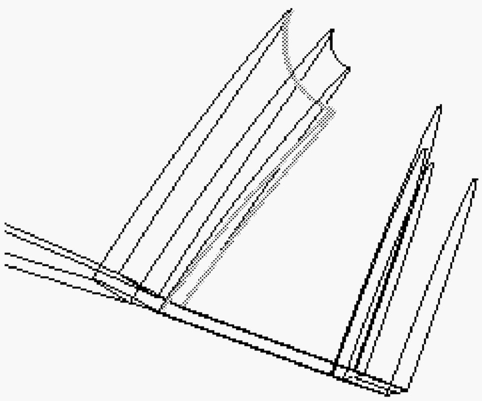


Figure 4 - Gaps Between Edges

At this vertex on the inside fillet one of the edges (top) has significant gaps with the other two--over 1 mm! Source - www.iti-oh.com.

-
- Sliver face (Figure 5)

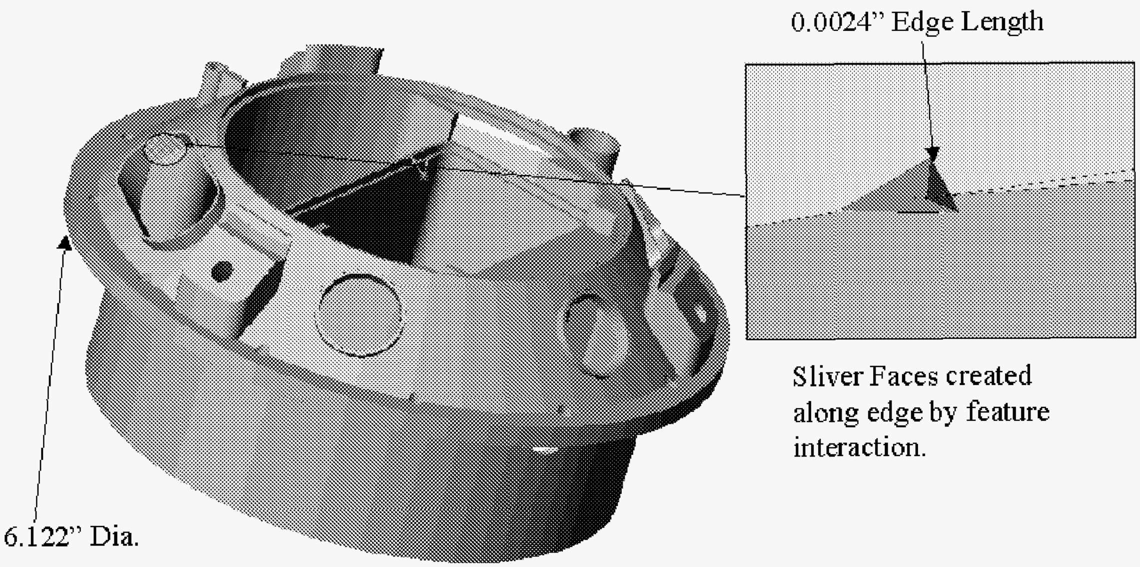


Figure 5 - Example of a Sliver Face Error

-
- Skins added to design surfaces
- Zero Area Faces
- Points not on a curve – hanging out in space

Topological Errors

- Surface vector reversal on complex surfaces
- Non-manifold solid
- Conflicts between non-manifold and manifold topologies
- Conflicts in surface normals – external loop should wrap around a periphery of a surface
- Excessive number of external loops attached to a boundary

Accuracy Specifications

Changing the accuracy specification from the default setting to a more stringent accuracy setting can cause 3-D MCAD model errors, especially in complex features that are generated through the use of approximation algorithms. These problems include:

- Gaps between surface edges
- Rounded corners becoming square
- Models not regenerating
- Protrusions (posts) appearing on models that are not design features (Figure 6)

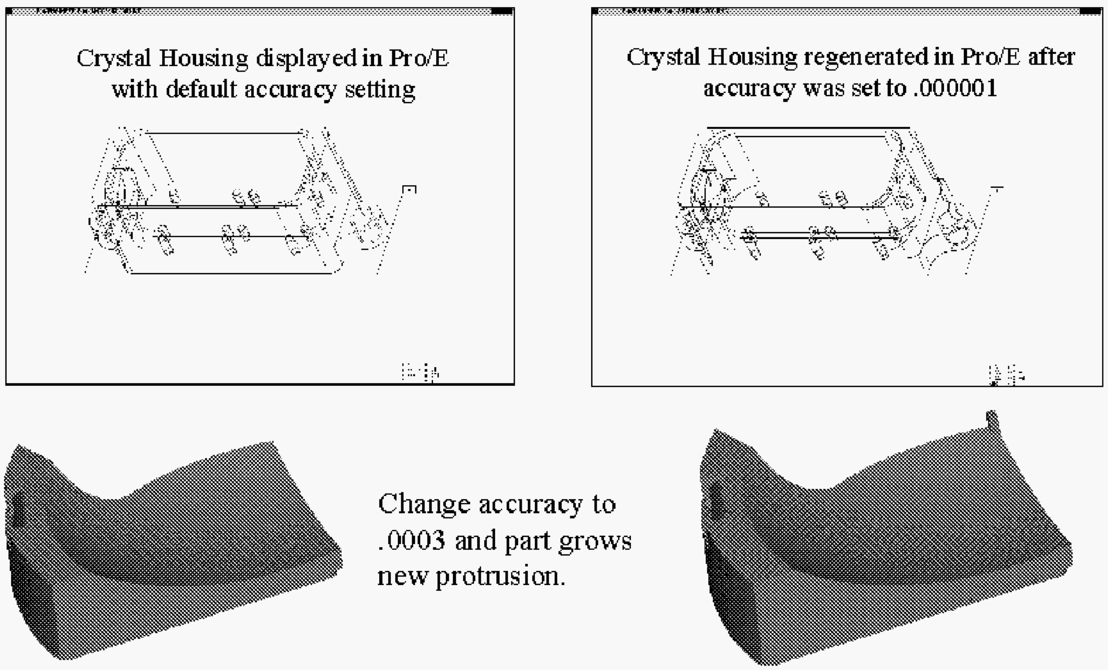


Figure 6 - Example of Accuracy Settings Causing Solid Model Shape Ambiguities

Sequencing Problems

Survey respondents indicated that manufacturing engineers frequently recreate solid MCAD models in order to sequence the feature specifications in the order of the production processes required to manufacture the part. MCAD solid models are aligned with the sequence manufacturing processes to facilitate process planning and NC programming processes.

2. Translation Errors

Translations of 3-D MCAD models from original formats to the formats used by a CAE, CAM, or CAPE application often create errors in the translated 3-D models. These errors are caused by failures to adhere to industry data transfer standards and ambiguity/oversight problems in industry data transfer standards.

As shown in Table 5, integrated MCAD/CAM applications developed by a single vendor are inherently compatible and the transfer of current version 3-D MCAD model data between these applications typically results in perfect translations with no errors. Furthermore, translations of MCAD data transferred between applications using the same 3-D geometric modeler (e.g. ACIS and Parasolid) are often completed with minimal errors. There is some concern in the industry that as solid model software quickly evolves through multiple versions that legacy models will not be translated as perfectly by future versions of the vendor's 3-D MCAD/CAM applications.

One survey respondent informed that neutral translators incorporating the IGES or STEP data transfer standard are successful in converting MCAD files, if the CAD designer is knowledgeable of and adheres to the applicable standard. If designers do not adhere to the IGES or STEP standard, then frequent translation errors were reported. The use of direct translators also incurs mixed results depending upon the CAD/CAM systems and translator applications used by the manufacturer.

Table 5 - Success of Various Data Transfer Scenarios

Types of MCAD Data Transfer	Benefits/Problems
Direct Transfer of Native Files Between Applications Developed by the Same Vendor	Perfect Transfer – No Errors
File Transfer Between Applications Using Same Geometric Modeler	Minimal Errors or Loss of Data
IGES or STEP Translation	Mixed Results Depending Upon Conformance to Standards
Third Party Direct Translation	Mixed Results Depending On 3rd Party and Source/Target Applications

3-D MCAD model data translation errors reported by the survey respondents include:

- Gaps Between Surface Edges
- Appearance of Unexpected Features
- Complete Loss Of Feature Data
- Partial Loss Of Feature Data (Especially Tolerance Data)
- Misrepresentation Of Feature Geometry

3. Strategies For Solving Interoperability Problems

The various strategies identified in the user survey for handling the basic interoperability problems of CAD/CAM applications are presented briefly in Table 6. Each strategy has tradeoffs in either solving data transfer problems or implementing best-of-breed CAD/CAM system functionality. None of these strategies have been successful in accomplishing both objectives.

Table 6 - Effectiveness and Problems of Strategies for Coping with CAD/CAM Interoperability Problems

Strategy	Benefits	Problems
Use Same Vendor for All CAD/CAM Applications	Perfect File Transfers	Lack of Functionality
Make Designers Conform to Translation Standards (IGES/STEP)	Good File Transfers	Lack of Design Flexibility
Implement Best of Breed CAD/CAM Applications	Effective CAD/CAM Functionality	Expend Resources Checking, Healing, and Rebuilding MCAD Models

4. Impact of 3-D MCAD Model Integrity Problems On Downstream Manufacturing And Quality Processes

Original and translated 3-D MCAD model imperfections result in excessive delays and labor finding and correcting these problems as shown in Figure 7. Respondents informed that these delays can range from 1 hour to a day or more. These delays occur with the original design and for each design revision process compounding the cost of 3-D MCAD model interoperability problems.

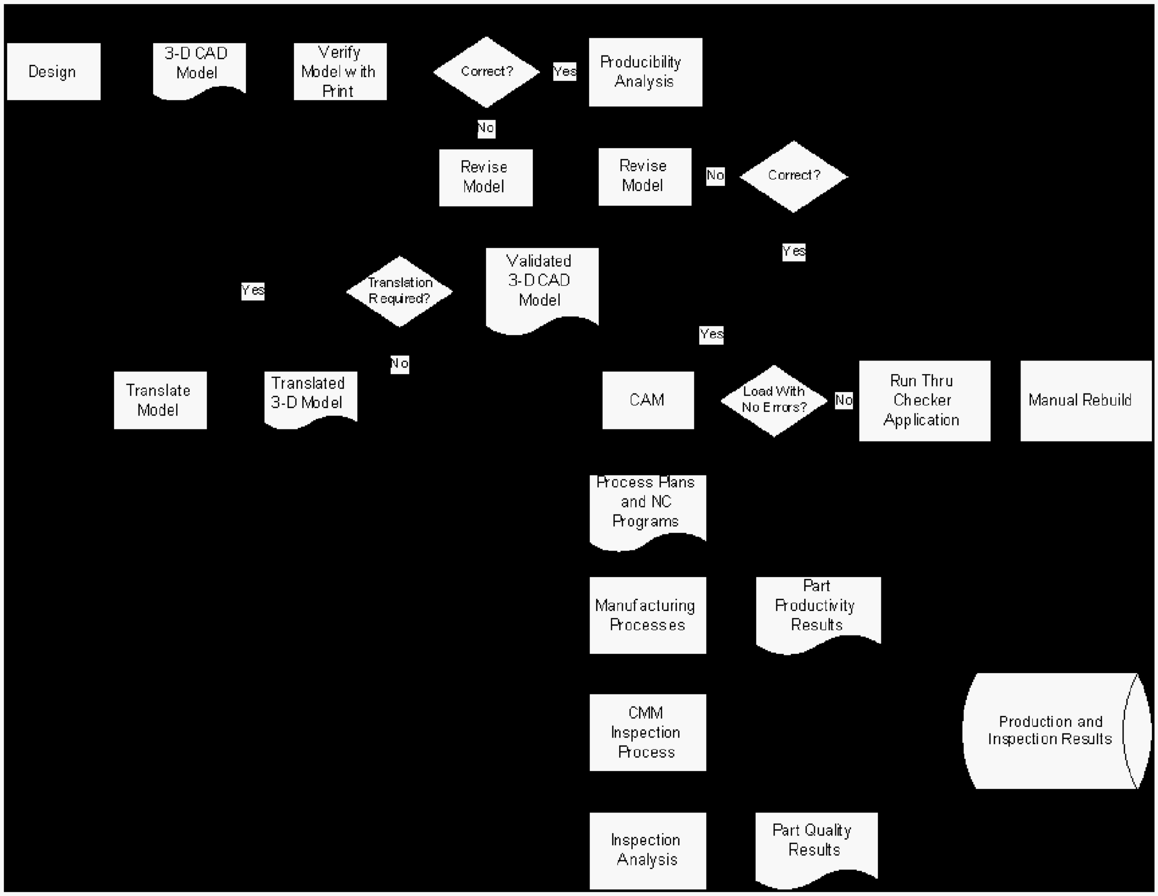


Figure 7 - Current Product Development Process

III. CONCLUSIONS

This section provides the conclusions and recommendations for solving the interoperability problems associated with using 3-D MCAD models in the downstream processes of manufacturing and quality.

A. **CAD PROCEDURE STANDARDS AND GUIDELINES**

The high number of original 3-D MCAD model errors identified by our survey respondents suggests that there is a need to develop MCAD procedure standards and guidelines. These standards and guidelines need to be developed initially in a neutral format and then applied to individual MCAD vendor solutions. The structure of the MCAD procedure standards and guidelines should include:

- File Definitions

- Format
- Parameters
- Other assembly part interfacing features specifications
- Design Configuration Control
- Work Area
- Datum Surfaces
- Coordinate System
- Part Axis
- Layers
- Procedures
- Raw Material Shapes
- Roughing
- Features Creation

A. STEP STANDARD DEVELOPMENT SHOULD BE SUPPORTED

The STEP standard administrated by the ISO and NIST has the best potential for widespread acceptance based upon its international acceptance and MCAD solid model focus; therefore,

support and participation in development of this standard is a highly recommended approach for achieving CAD/CAM interoperability. AlliedSignal and CAM-I can facilitate development of the MCAD/CAM portion of the STEP standard by

- Reviewing and participating in standard development to determine the suitability and comprehensiveness of the STEP standards in solving MCAD/CAM interoperability problems,

- Suggesting improvements, and
- Verifying the effectiveness of STEP standards implementation in commercial applications.

A. STEP SHOULD INCLUDE DIMENSIONAL INSPECTION INFORMATION

The STEP standard should include specifications for the transfer of data needed to manage the dimensional inspection of solid parts or assemblies. The scope of these management processes involves the administration, planning, and execution of dimensional inspection as well as the analysis and archiving of inspection results. Providing only the nominal specifications of features in solid MCAD models is inadequate direction for the manufacture and design conformance of products. Currently, tolerance information is passed to manufacturing and quality through workaround processes that require excessive labor, cost, and more importantly time to deliver products to market. Requirements for this standard should include, but not necessarily limited to:

- Capability to specify metrology requirements in CAX (computer aided design, engineering, manufacturing, process engineering & analysis)
- Capability to perform unambiguous transfer of metrology requirements
- Capability to capture complex geometry as features in CAX systems
- An abstract model-based inspection language
- Exchange representations of uncertainty estimates between systems
- Common formats for representing equipment performance, data output, analysis results
- An accepted set of definitions and interpretations of features & tolerances
- Common representations of set-up, fixturing, compensation, & environmental information

A. PRODUCT FEATURE DEFINITION STANDARD

One issue causing MCAD/CAM interoperability problems is the inadequacy of feature definition standards. Industry publications cite that the IGES standard has ambiguity problems arising offering multiple standards to define individual features. The STEP standard suffers from deficiencies in comprehensive feature geometry and attribute definitions. It would much simpler for designers and manufacturing personnel, if there were a universal, vendor-neutral standard for the definition of product features that is acceptable and applicable to all processes involved in the product development cycle. The benefits of a universal product feature definition standard include the ability to improve the automation of

MCAD/CAM processes and improved communication and collaboration capabilities between all participants in the product development process flow.

Following an object-oriented design approach, standards for feature objects could be developed to contain all of the attributes necessary to design, manufacture, and inspect products. These feature objects could be a set of related, discrete features such as o-ring grooves or they could be flexible feature objects for variable construction features such as pockets that require the entry of parametric data by users. Design related feature attributes would include design intent data for the feature such as functionality of the part itself and functionality with the engaged features of other parts in the assembly. Design functionality requirements could then be used to specify tolerance requirements for feature geometry; thereby providing an objective basis for design tolerances. Manufacturing and inspection related attributes could include the process plans and NC programs required for specifying the tools, fixtures, and machine movements needed to machine and then inspect part features.

The advantages of design feature objects are enormous. With standard feature objects, designers could create designs faster and provide more information to the downstream analysis, manufacturing and quality processes. More importantly, with all parties using the same feature definitions, feedback information such as manufacturing and inspection process time and costs can be provided to the designer as standard feature attribute data in the design feature selection and configuration process.

E. Future Uses of MCAD Models in Manufacturing and Quality Processes

When the MCAD designer of the future begins a part design, he starts with a standard file format and workspace template that is automatically loaded with information from the designer's personal information object including data identifying himself, his department, and location. He also enters part design intent information including part functions and specifications for interfacing with features of other parts. Then, the designer typically selects a raw material shape from an inventory of materials, including include castings or forgings, maintained by the purchasing department or, if necessary, from the inventories of approved vendors. The designer can also create a new raw material shape, if required by the part design.

When the designer starts to create part features, he can select and configure a master feature object to quickly and more thoroughly define the feature. For example, instead of removing a ring of material from a shaft to create an o-ring groove and having to look up the tolerances required to provide the class of fit required for a particular o-ring, the designer will request the o-ring object and review:

- design characteristics of standard o-rings,
- manufacturing costs to create the o-ring groove, and
- inspection costs to verify conformance.

Once the designer selects the desired o-ring and enters required operating parameters, the o-ring object will then automatically create the o-ring groove design feature incorporating all of the dimensional, tolerance, and design intent specifications for the o-ring groove. Selection of the standard o-ring and groove feature also automatically specifies the process steps, NC program routines, and costs required to manufacture and inspect the feature. Furthermore, selection of the o-ring groove feature also triggers CAE applications loaded in memory to perform finite element analysis and assembly fit analysis. In addition, an intelligent manufacturing assistant reviews the manufacturability of the sequence of feature creation steps and delivers a prompting message when it identifies an alternative sequence that is more compatible with standard manufacturing procedures.

The system assigns a unique identifier for each feature as it is created and added to the MCAD model design. This provides the key required to associate features within the MCAD solid model, manufacturing/quality process plans and NC programs so future design revisions can be accomplished with modifications of the portions of manufacturing plans and programs associated directly with the changed feature(s).

When the MCAD solid model design is complete, the designer saves the file in the product design repository, updates the engineering change number of the product and releases it for manufacturing (Figure 8). A workflow message is sent to the CAM applications to automatically generate manufacturing and inspection process plans and NC programs as directed by feature object attributes. For CAD/CAM systems operating in the Windows environment, the MCAD design database is queried by the CAM application through an OLE interface without actual transfer of the MCAD file. The MCAD file does not have to be translated, since the design is comprised of a compilation of standard feature objects with manufacturing and inspection related attributes specifying the process plans and NC programs required to machine and inspect the part feature. Manufacturing and quality engineers that previously spent most of their time developing process plans and NC programs for each part, now spend their time reviewing and optimizing the performance of manufacturing and inspection automation strategies and NC program templates.

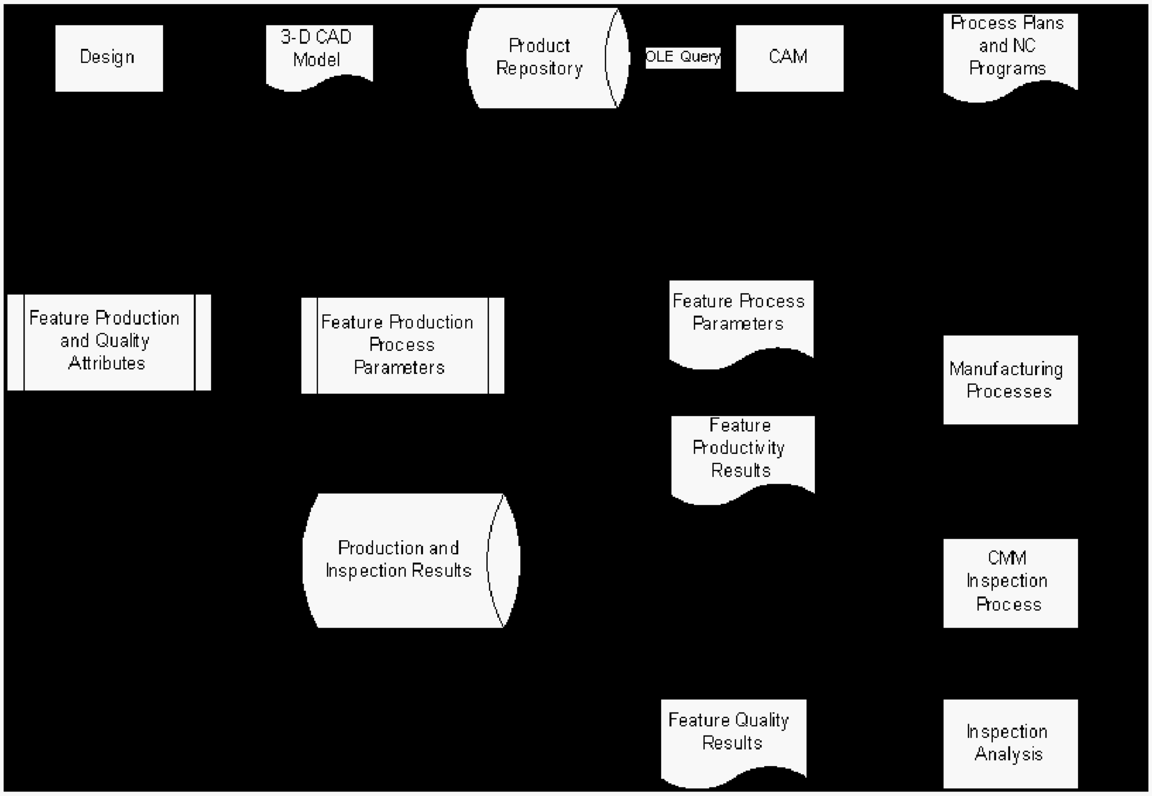


Figure 8 - Future Product Development Process

Since NC machining and inspection programs will by structured by part features, shop floor systems will be capable of collecting production and quality data for individual product features. This will provide the detailed level of granularity needed to automatically collect production process parameters and quality results for individual product features. Production process parameters data such as tool offsets and speed and feed overrides used to generate individual product features and CMM inspection results can be analyzed by manufacturing engineers to evaluate and optimize the effectiveness of process plans and NC program templates for various classes of features. Product feature manufacturing requirements and risk attributes can be updated automatically and fed to design engineers to assure product design manufacturability.

Appendices

Appendix A

Companies and Participants Included in Survey

Company	Participants
AlliedSignal	
Lockheed Martin Energy Systems	
Rockwell Collins Inc.	

Appendix B

Survey Results Analysis

Summary Analysis of Impact of 3-D MCAD Model Integrity on Manufacturing and Quality Processes

Survey

1.
2. Which of the following 3-D Mechanical Computer-Aided Design (MCAD) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used for design collaboration? If a system is not listed, enter the response on a blank line.

MCAD System	Frequency of Response – Purpose (e.g. Conceptual Design, Final Design)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Pro/ENGINEER	1 - Final Design	90%	STEP
	1 - Conceptual Through Final Design	90%	N/A
	1 - Conceptual Through Final Design	5%	Native, STEP, IGES
CATIA	1 - Customer data visualization, integration and conversion	20 %	Native, STEP, IGES
	Customer required documentation		
SolidWorks	1 - Final Design, Conceptual Design	10%	STEP
	1 - Conceptual Design thru Final Design	10%	N/A
I-DEAS	Conceptual design , final design and documentation	40%	Native, STEP, IGES
Unigraphics	1 - Conceptual design ,final design and documentation	55%	Native, STEP, IGES
Solid Edge			
AutoCAD	View Original drawing from Customer (if importing to Pro_E fails)	???	N/A
MicroCadam			
ACIS			

Raster X	For scanning and performing minor modifications (on notes) of legacy designs	100%	NA
ICEMDDN			

- Which of the following 3-D Mechanical Computer-Aided Engineering (CAE) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAE System	Frequency of Response – Purpose (e.g. Finite Element Analysis, Fit Analysis)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Pro/MECHANICA			
CATIA			
SolidWorks			
IDEAS SDRC	1 - Finite Element Analysis	?	STEP
	1 - Finite Element Analysis Vibration	100%	
Unigraphics			
Solid Edge			
AutoCad			
MicroCadam			

ANSYS			
ACIS	1 - Geometric Automation Program for Feature Based Tolerancing (FBTol)	?	STEP
Altair HyperWorks			
ESP FEMAP			
MSC			
Sandia Package Based on ACIS	1 - Simulation	?	
Allied Signal (ACIS) Feature Based Tolerance Husk	1 - Associate tolerances with design features	?	
ANSYS	1 - FEM Thermal, Structural	30%	
Pacific Numerics	1 - FEM Thermal	40%	
Flowtherm	1 - FEM Thermal	30%	
Other	1 - Variety of CAE Analysis	100%	IGES

- Which of the following 3-D Mechanical Computer-Aided Manufacturing/Quality (CAM) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAM System	Frequency of Response – Purpose (e.g. Process Planning, NC Programming, CMM Programming)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)

Pro/Manufacturing	1 - Numerical Control Programming	10%	Direct Import
CATIA			
SolidWorks			
I-DEAS			
Unigraphics	1 - Process Planning;	?	
	NC Programming,		
	Create 'In-Process' Solid Models	100%	STEP, Parasolid
	1 - NC Programming		
ACIS			
CimStation	1 - CMM DMIS Programming	100%	Direct Import
	1 - CMM Programming	10%	
MasterCam		?	
SurfCam	1 - Numerical Control Programming	10%	Direct Import
MacNeal-Schwendler Corp			
DesignSpace			
CNC Software, Inc.			
ESPRIT			
Vericut, CG Tech	1 - NC Program Validation	100%	
Allied Signal (ACIS) Feature Based Machining	1 - Process Planning, NC Programming	?	
Anvil 5K/Express	1 - Numerical Control Programming	80%	IGES & Direct

CIPS	1 - YZ Programming	100%	Direct Import

- Which of the following 3-D MCAD checker applications do you use, for what purpose(s), the % of that purpose performed with the application, and the type of file checked? If an application is not listed, enter your response on a blank line.

Checker Application	Frequency of Response - General and/or Specific Types of Errors Checked For	Use %	MCAD Model Type Checked (e.g. original file, STEP file, IGES file)
ITI CAD/IQ		?	
Prescient Design/QA		?	
Prescient GeometryQA			
Allied Signal (ACIS) Feature Based Tolerance Husk	1 - Verify feature tolerances and fits	?	

- Which of the following 3-D MCAD design healer applications do you use, for what purpose(s), the % of that purpose performed with the application, and the and the type of file healed? If an application is not listed, enter the response on a blank line.

Healer Application	Frequency of Response - General and/or Specific Types of Errors Healed	Use %	MCAD Model Type Healed (e.g. Original file, STEP file, IGES file)
ITI Fixer Upper	1	?	
ACIS Healing Husk	1	?	
Compunix			
Geometric Software Solutions			
FEGS CADfix			
Spatial Technology	1	?	

- Which of the following geometry inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, which features encounters these problems most frequently and how to you find and correct these errors? If a geometric error is not listed, enter the response on a blank line.

Geometry Inaccuracy	Frequency of Response - Approx. % of Occurrence	Features That Encounter the Problem Most Frequently	How do you Identify This Problem?	How do you Resolve This Problem?
Gaps between faces	1 - ? 1 - 0.5	Blends, Fillets, and Rounds Freeform modeling	Use checkers on original model Validity check or during N/C programming	Manual correction; Run solid models through Spatial's Healer Remodel area/s with problem or remodel entire part
Splinter faces	1 - ? 1 - 0.5	Blends, Fillets, and Rounds Freeform modeling	Use checkers on original model Validity check or during N/C programming	Manual correction; Run solid models through Spatial's Healer Remodel area/s with problem or remodel entire part
Gaps in the edges of	1 - ?		Use checkers on	Manual correction;

surface intersections			original model	Run solid models through Spatial's Healer
	1 - 0.5	Freeform modeling	Validity check or during N/C programming	Remodel area/s with problem or remodel entire part
Skins added to design surfaces			Use checkers on original model	Manual correction; Run solid models through Spatial's Healer
Zero Area Faces			Use checkers on original model	Manual correction; Run solid models through Spatial's Healer
Curves not lying on surfaces creating a gap			Use checkers on original model	Manual correction; Run solid models through Spatial's Healer
Points not on a curve – hanging out in space			Use checkers on original model	Manual correction; Run solid models through Spatial's Healer

- Which of the following topological inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, how to you find and correct these errors? If a topological error is not listed, enter the response on a blank line.

Topological Inaccuracy	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Surface vector reversal on complex surfaces	1 - ?	Visual inspection	Manual correction; Use ACIS Healer
	1 - 0.5	Visually	Redefine the vector
Conflicts between non-manifold and manifold topologies	1 - ?	Visual inspection	Manual correction; Use ACIS Healer
Conflicts in surface normals – external loop should wrap around a periphery of a surface		Visual inspection	Manual correction; Use ACIS Healer
Excessive number of external loops attached to a boundary		Visual inspection	Manual correction; Use ACIS Healer
Non-manifold solid	1 - 0.5	Software internal checks	Remodel the feature

- Which of the following problems occur when using the default accuracy setting of the MCAD system or increasing the accuracy level of models after creation of the model at the default accuracy? What is the approximate frequency of occurrence, how to you find and correct these errors? If an error is not listed, enter the response on a blank line.

Problem Description	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Rounded corners become square when accuracy level is increased	1 - 50%	Visual inspection	Manual correction; Lower accuracy level; ITI Fixer Upper; ACIS Healer; Suppress Fillets and Re-export
Some models will not regenerate when accuracy level is increased	1 - 50%	NA	Manual correction; ITI Fixer Upper
Protrusions (posts) sometimes form when accuracy level is increased	1 - >5%	CAD/IQ Checker	Manual correction

- What kinds of problems are caused by the transfer of 3-D MCAD models from a CAD system to another CAD system or downstream CAM system using a different model scaling system (e.g. metric versus English)? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Boolean operation failures	1 - ?	Visual Inspection	Manual correction
Inverted surfaces	1 - ?	Visual Inspection	Manual correction
Skins appearing at ends of cylinders	1 - ?	Visual Inspection	Sharpen the CIMStation resolution, which causes the model to get larger and slow system performance
Face-Face Intersections	1 -1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part
Tiny surfaces	1 - 1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part
Splinters	1 - 1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part

- Do you have problems caused by different representations of geometry and topology used by the various CAD systems and downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Translated parts lose specific feature definitions	1 - ?	Visual inspection	Manual correction
	1 – 25	Cannot drive N/C programming from features	Creating N/C program by with more manual methods
Boolean operations failures	1 - ?	Visual inspection	Manual correction
NC path plan will not compute	1 - ?	Visual inspection	Manual correction
Inprocess shapes will not generate	1 - ?	Visual inspection	Manual correction
STEP translated parts imported into Pro/E become a single feature solid model that is not modifiable and unusable.	1 - ?	Visual inspection	Manual correction
Counterbore direction reversal	1 - ?	Visual inspection	Manual correction
Hole edge definition is two half arcs when using parasolid to import into Unigraphics (CAM) from SDRC	1 – 25	Cannot drive N/C programming from features	Creating N/C program by with more manual methods
NC path plan will not	2	Model changes that	Redo N/C programming for

compute		have been made by replacing features instead of changing features	that area

- Do you have any of the following problems caused by incorrect design procedures or design procedures that are incompatible with downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Use of cut-through command rather than a cut-to command to remove a section from a feature causing geometry errors and sliver faces	1 - ? 100%	CAD/IQ and Design QA to check models Inherent to Pro/E	Use a healer; Manual correction Work-Arounds and by Using Other CAM systems such as Anvil Express
Design procedure of creating two features by cutting a section out of a larger initial feature causes the CMM programming application to recognize only one feature when two features need to be inspected	1 - ?	Visual Inspection	Manual Correction

- What other original or translated CAD model imperfections have you experienced? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Frequency of Response - Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Downstream CAM processes cannot import CAD design changes and must be completely recreated with each design modification	1 - ?	Visual Inspection	Manual Creation
Model constructed from design intent perspective instead of manufacturing perspective	1 - 75%	N/A	Requires creating additional Manufacturing Model

- Do you experience any of the following errors caused by feature interactions such as cutting features leaving difficult to detect sliver faces? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Frequency of Response – Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Slivers represent unexpected features creating unneeded process steps in manufacturing/ quality processes	1 - ? 0.5	CAD/IQ and Design QA to check models Validity check, subsequent operations	Use a healer; Manual correction Remodel area with problem/s
Small edges round to zero causing Boolean operation failures	1 - ?	CAD/IQ and Design QA to check models	Use a healer; Manual correction

- Do you experience loss of tolerance associations to features in model translations from system to the next? Yes
- Use original part drawings until the FB Tolerance application is implemented fully
- This is a non issue with our facility. Our inspection part programming tools utilize the Pro/E model and not a translation. The Pro/E model can carry the association of the tolerance with a feature
- Only when the downstream system has less precision. In this case, nothing can be done to resolve

Appendix C

Individual Interviews

Impact of 3-D MCAD Model Integrity on Manufacturing and Quality Processes

Survey Questionnaire

Name: Date: 4 Aug 1999

Company: Rockwell Collins Inc. Dept.: Mechanical Design Support

- Which of the following 3-D Mechanical Computer-Aided Design (MCAD) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used for design collaboration? If a system is not listed, enter the response on a blank line.

MCAD System	Purpose – (e.g. Conceptual Design, Final Design)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Unigraphics	Conceptual design ,final design and documentation	55	Native, STEP, IGES
I-DEAS	Conceptual design , final design and documentation	40	Native, STEP, IGES
Pro/ENGINEER	Conceptual design and final design	5	Native, STEP, IGES
CATIA	Customer data visualization, integration and conversion Customer required documentation	20	Native, STEP, IGES

- Which of the following 3-D Mechanical Computer-Aided Engineering (CAE) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAE System	Purpose – (e.g. Finite Element Analysis,Fit Analysis)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
ANSYS	FEM Thermal, Structural	30	
Pacific Numerics	FEM Thermal	40	
Flowtherm	FEM Thermal	30	
IDEAS SDRC	FEM Vibration	100	

- Which of the following 3-D Mechanical Computer-Aided Manufacturing/Quality (CAM) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAM System	Purpose – (e.g. Process Planning, NC Programming, CMM Programming)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Unigraphics	NC Programming	100	STEP, Parasolid
Vericut, CG Tech	NC Program Validation	100	

- Which of the following 3-D MCAD checker applications do you use, for what purpose(s), the % of that purpose performed with the application, and the type of file checked? If an application is not listed, enter your response on a blank line.

Checker Application	General and/or Specific Types of Errors Checked For	Use %	MCAD Model Type Checked (e.g. original file, STEP file, IGES file)
none			

- Which of the following 3-D MCAD design healer applications do you use, for what purpose(s), the % of that purpose performed with the application, and the type of file healed? If an application is not listed, enter the response on a blank line.

Healer Application	General and/or Specific Types of Errors Healed	Use % 	MCAD Model Type Healed (e.g. Original file, STEP file, IGES file)
Unigraphics Tolerant Modeler Fault Correction	Body is inside out Vertex not on curve Edge reversed Vertex not on surface Edge not on surface Inconsistent loop Non G1-continuous	100 (of data designed using Unigraphics	UG native file, STEP

- Which of the following geometry inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, which features encounters these problems most frequently and how to you find and correct these errors? If a geometric error is not listed, enter the response on a blank line.

Geometry Inaccuracy	Approx. % of Occurrence	Features That Encounter the Problem Most Frequently	How do you Identify This Problem?	How do you Resolve This Problem?
Gaps between faces	0.5	Freeform modeling	Validity check or During N/C programming	Remodel area/s with problem or remodel entire part
Splinter faces	0.5	Freeform modeling	Validity check or During N/C programming	Remodel area/s with problem or remodel entire part
Tiny objects	0.5	Freeform modeling	Validity check or During N/C programming	Remodel area/s with problem or remodel entire part

- Which of the following topological inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, how to you find and correct these errors? If a topological error is not listed, enter the response on a blank line.

Topological Inaccuracy	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Surface vector reversal on complex surfaces	0.5	Visually	Redefine the vector
Non-manifold solid	0.5	Software internal checks	Remodel the feature

- Which of the following problems occur when using the default accuracy setting of the MCAD system or increasing the accuracy level of models after creation of the model at the default accuracy? What is the approximate frequency of occurrence, how to you find and correct these errors? If an error is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
none			

- What kinds of problems are caused the transfer of 3-D MCAD models from a CAD system to another CAD system or downstream CAM system using a different model scaling system (e.g. metric versus English)? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Face-Face Intersections	1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part
Tiny surfaces	1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part
Splinters	1	Validity checks and N/C programming errors	Remodel area/s with problem or remodel entire part

- Do you have problems caused by different representations of geometry and topology used by the various CAD systems and downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Translated parts lose specific feature definitions	25	Cannot drive N/C programming from features	Creating N/C program by with more manual methods
Hole edge definition is two half arcs when using parasolid to import into Unigraphics (CAM) from SDRC	25	Cannot drive N/C programming from features	Creating N/C program by with more manual methods
NC path plan will not compute	2	Model changes that have been made by replacing features instead of changing features	Redo N/C programming for that area

- Do you have any of the following problems caused by incorrect design procedures or design procedures that are incompatible with downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Use of cut-through command rather than a cut-to command to remove a section from a feature causing geometry errors and sliver faces			
Design procedure of creating two features by cutting a section out of a larger initial feature causes the CMM programming application to recognize only one feature when two features need to be inspected			

- What other original or translated CAD model imperfections have you experienced? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?

- Do you experience any of the following errors caused by feature interactions such as cutting features leaving difficult to detect sliver faces? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Slivers represent unexpected features creating unneeded process steps in manufacturing/ quality processes	0.5	Validity check, subsequent operations	Remodel area with problem/s

- Do you experience loss of tolerance associations to features in model translations from system to the next? _Y_
- How do you resolve this problem?
- Only when the downstream system has less precision. In this case, nothing can be done to resolve
- Do you experience loss of higher level information in model translations from system to the next such as:
- Feature definitions?_Y_
- Assembly definitions?_N_
- Dimensions and tolerances in a form that is editable?_Y_
- Manufacturing features not associated directly with design features?_Y_
- Bill of material data?_Y_

Impact of 3-D MCAD Model Integrity on Manufacturing and Quality Processes

Survey Questionnaire

Name: Date: August 3, 1999

Company: Lockheed Martin Energy Systems Department: ADAPT Program

- Which of the following 3-D Mechanical Computer-Aided Design (MCAD) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used for design collaboration? If a system is not listed, enter the response on a blank line.

MCAD System	Purpose – (e.g. Conceptual Design, Final Design)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Pro/ENGINEER	Conceptual Design thru Final Design	90%	N/A
CATIA			
SolidWorks	Conceptual Design thru Final Design	10%	N/A
I-DEAS			
Unigraphics			
Solid Edge			
AutoCAD			
MicroCadam			
ACIS			
Raster X			
ICEMDDN			

- Which of the following 3-D Mechanical Computer-Aided Engineering (CAE) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAE System	Purpose – (e.g. Finite Element Analysis,Fit Analysis)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Pro/MECHANICA			
CATIA			
SolidWorks			
IDEAS SDRC			
Unigraphics			
Solid Edge			
AutoCad			
MicroCadam			
ANSYS			
ACIS			
Altair HyperWorks			
ESP FEMAP			
MSC			

Sandia Package Based on ACIS			
Allied Signal (ACIS) Feature Based Tolerance Husk			
Other	Variety of CAE Analysis	100%	IGES

- Which of the following 3-D Mechanical Computer-Aided Manufacturing/Quality (CAM) systems do you use, for what purpose(s), the % of that purpose performed with the application, and the transfer process used to load the MCAD model? If a system is not listed, enter the response on a blank line.

CAM System	Purpose – (e.g. Process Planning, NC Programming, CMM Programming)	Use %	MCAD Model Import Process (e.g. direct import, STEP, IGES)
Pro/Manufacturing	Numerical Control Programming	10%	Direct Import
CATIA			
SolidWorks			
I-DEAS			
Unigraphics			
ACIS			
CimStation			
MasterCam			
SurfCam	Numerical Control Programming	10%	Direct Import

MacNeal-Schwendler Corp			
DesignSpace			
CNC Software, Inc.			
ESPRIT			
Vericut, CG Tech			
Allied Signal (ACIS) Feature Based Machining			
ICEMDDN			
Anvil 5K/Express	Numerical Control Programming	80%	IGES & Direct
CimStation	CMM Programming	100%	Direct Import
CIPS	YZ Programming	100%	Direct Import

- Which of the following 3-D MCAD checker applications do you use, for what purpose(s), the % of that purpose performed with the application, and the type of file checked? If an application is not listed, enter your response on a blank line.

Checker Application	General and/or Specific Types of Errors Checked For	Use %	MCAD Model Type Checked (e.g. original file, STEP file, IGES file)
ITI CAD/IQ			
Prescient Design/QA			
Prescient GeometryQA			
Allied Signal (ACIS) Feature Based Tolerance Husk			

- Which of the following 3-D MCAD design healer applications do you use, for what purpose(s), the % of that purpose performed with the application, and the and the type of file healed? If an application is not listed, enter the response on a blank line.

Healer Application	General and/or Specific Types of Errors Healed	Use %	MCAD Model Type Healed (e.g. Original file, STEP file, IGES file)
ITI Fixer Upper			
ACIS Healing Husk			
Compunix			
Geometric Software Solutions			
FEGS CADfix			
Spatial Technology			

- Which of the following geometry inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, which features encounters these problems most frequently and how to you find and correct these errors? If a geometric error is not listed, enter the response on a blank line.

Geometry Inaccuracy	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Gaps between faces			
Splinter faces			
Gaps in the edges of surface intersections			
Skins added to design surfaces			
Zero Area Faces			
Curves not lying on surfaces creating a gap			
Points not on a curve – hanging out in space			

- Which of the following topological inaccuracies do you find in your 3-D MCAD models? What is the approximate frequency of occurrence, how to you find and correct these errors? If a topological error is not listed, enter the response on a blank line.

Topological Inaccuracy	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Surface vector reversal on complex surfaces			
Conflicts between non-manifold and manifold topologies			
Conflicts in surface normals – external loop should wrap around a periphery of a surface			
Excessive number of external loops attached to a boundary			

- Which of the following problems occur when using the default accuracy setting of the MCAD system or increasing the accuracy level of models after creation of the model at the default accuracy? What is the approximate frequency of occurrence, how to you find and correct these errors? If an error is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Rounded corners become square when accuracy level is increased			
Some models will not regenerate when accuracy level is increased			
Protrusions (posts) sometimes form when accuracy level is increased			

- What kinds of problems are caused the transfer of 3-D MCAD models from a CAD system to another CAD system or downstream CAM system using a different model scaling system (e.g. metric versus English)? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Boolean operation failures			
Inverted surfaces			
Skins appearing at ends of cylinders			

- Do you have problems caused by different representations of geometry and topology used by the various CAD systems and downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Translated parts lose specific feature definitions			
Boolean operations failures			
NC path plan will not compute			
Inprocess shapes will not generate			
STEP translated parts imported into Pro/E become a single feature solid model that is not modifiable and unusable.			
Counterbore direction reversal			

- Do you have any of the following problems caused by incorrect design procedures or design procedures that are incompatible with downstream CAM processes? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Use of cut-through command rather than a cut-to command to remove a section from a feature causing geometry errors and sliver faces	100%	Inherent to Pro/E	Work-Arounds and by Using Other CAM systems such as Anvil Express
Design procedure of creating two features by cutting a section out of a larger initial feature causes the CMM programming application to recognize only one feature when two features need to be inspected			

- What other original or translated CAD model imperfections have you experienced? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Downstream CAM processes cannot import CAD design changes and must be modified with each design modification			
Model constructed from design intent perspective instead of manufacturing perspective	75%	N/A	Requires creating additional Manufacturing Model

- Do you experience any of the following errors caused by feature interactions such as cutting features leaving difficult to detect sliver faces? What is the approximate frequency of occurrence, how to you find and correct these errors? If a problem is not listed, enter the response on a blank line.

Problem Description	Approx. % of Occurrence	How do you Identify This Problem?	How do you Resolve This Problem?
Slivers represent unexpected features creating unneeded process steps in manufacturing/ quality processes			
Small edges round to zero causing Boolean operation failures			

- Do you experience loss of tolerance associations to features in model translations from system to the next? __
- How do you resolve this problem?
- This is a non issue with our facility. Our inspection part programming tools utilize the Pro/E model and not a translation. The Pro/E model can carry the association of the tolerance with a feature
- Do you experience loss of higher level information in model translations from system to the next such as:
- Feature definitions?__
- Assembly definitions?__
- Dimensions and tolerances in a form that is editable?__
- Manufacturing features not associated directly with design features?__

- Bill of material data?__

Appendix B

DesignQA Software Tool - Example Model Qualification Standards Criteria

Appendix C

Implementing Six Sigma in Engineering Design[3]

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(Now http://www.planetcad.com/ PlanetCAD, Inc., 2520 55th Street, Boulder, CO 80301).

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Six Sigma

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May 1999

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Implementing Six Sigma in Engineering Design

By

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Introduction

In the early part of the twentieth century, Henry Ford became famous (and wealthy) because of the innovations that he introduced in the automobile manufacturing process. These changes resulted in a short-term benefit to consumers (cars became affordable) and a long-term revolution that changed the world (the new manufacturing industries became the century's dominant economic force.) Today, manufacturing companies break new ground every day – not only on the manufacturing shop floor, but also in the engineering and design offices where the products are defined. To be sure, manufacturing processes continue to be improved, but the real leaps forward are being made in how new products are conceived and engineered.

As the evolution of manufacturing technologies unfolded in the latter part of the twentieth century, so did techniques to better understand and control the process of manufacturing. Using statistical techniques, product quality as a function of controllable steps in the manufacturing process, has now become one of the key drivers of corporate profitability. Indeed, product quality is a pervasive thread on any yardstick of competitive positioning, from time-to-market (quality initiatives reduce cycle times in product realization) to cost (rework and recalls can quickly eat into any profit margin.)

Six Sigma, the most prominent quality improvement methodology in practice, is so important to manufacturing enterprises that it has taken on a strategic corporate role. The 1998 annual report of the General Electric Company states:

‘We have invested more than a billion dollars in the [Six Sigma] effort, and the financial returns have now entered the exponential phase — more than three quarters of a billion dollars in savings beyond our investment in 1998, with a billion and a half in sight for 1999.” The report continues, “Every new GE product and service in the future will be "DFSS" — Designed For Six Sigma. These new offerings will truly take us to a new definition of "World Class." ‘

Source: General Electric Company 1998 Annual Report

The 1998 AlliedSignal annual report re-affirms that company’s commitment to this process:

‘Ailing businesses are routinely restored to health by using Six Sigma tools, and healthy ones are made healthier as we find new ways to satisfy customers and reduce costs.’

Source: AlliedSignal, Inc. 1998 Annual Report

At Raytheon, Six Sigma is viewed as a vehicle for strategic corporate growth:

‘At Raytheon, Six Sigma is more than a quantitative statistical measure of processes; it embraces every aspect of work, using a disciplined, fact-based approach to problem solving. It is a new way of thinking about work and customer value. It is also a powerful force to create one corporate culture. ‘

Source: Raytheon Corporation 1998 Annual Report

At Motorola, the Six Sigma pioneer, their commitment to this concept is unwavering, after many years of it’s implementation:

‘The Six Sigma[SM] quality process provided the foundation for much of the progress we achieved over the past decade. It remains a fundamental initiative in our corporation and is being adopted by other fine corporations. ‘

Source: Motorola Inc. 1998 Annual Report

Advances in technologies for the engineering design process have brought this part of the *product realization* process far forward enough to be ready for Six Sigma approaches for engineering. New design and engineering technologies have done for the engineering process what Henry Ford did for manufacturing. No longer is the development of a new model (or new product) the handiwork of a lone, skilled artisan. Now, teams of engineers and designers, using common tools and methodologies collaborate in a highly orchestrated process to conceptualize, refine, detail, specify, and build almost every common and uncommon product, from computer chips to toys.

The evolution of new work methods and tools for the engineering design process has resulted in the creation of an *engineering product*, namely the digital product model. This product can and should be subject to the rigor of a Six Sigma quality assurance process in much the same manner as a physical product would be. This engineering product, or *virtual product,* saves time in product development by eliminating the need for a physical mock-up, and allows for early detection of interferences between components, and a number of trade-off, or optimization studies.

The approach suggested here is to focus a Six Sigma program on the digital model, in addition to the Six Sigma programs for the manufactured product. This new quality focus will, by virtue of its intrinsic higher quality yield, also improve the product and process quality with respect to the manufactured product.

How much of a problem is the issue of quality of the *engineering product*, and is it worth the effort involved in a quality program? A major competitive force in the global manufacturing environment is "time-to-market." How, then does the quality of the engineering product affect this dimension of corporate competitiveness? Studies have shown that schedule risk is derived primarily from several common factors, including unintentional iterations, intentional iterations, completeness of activities and information, activity duration variances, among others. (Browning, T. R., *Sources of Risk in Complex System Development*, Proceedings of the Eighth Annual International Symposium of INCOSE, Vancouver, July 1998.) It is the category of "unintentional iterations" that is of most concern here, because the inability to control the engineering product quality is a major cause of unnecessary and unplanned iteration. Specifically, design mistakes (errors and omissions) cause not only delays due to time required for correction, but also consequential re-work in coupled and related activities.

It has also been shown that the cost of design errors increases dramatically, the later in the design/manufacturing cycle they are detected. In fact, the average cost of a design change made in the engineering phase (prior to release-to-manufacturing) is 10% of the cost of the same change if it is made after the design has been released to manufacturing. It has further been shown that the cost of the design change is only 1% of the same change if that change is made once the production run has begun (Figure 1.) Compounded with the dramatic increased costs along the progression of a product development life cycle, the cost of the average design change made *during the engineering design phase* is $3,500, based on cross-industry studies. (Finn, G.A., *Measuring and Managing Quality in the Engineering Design Process,* CATIA Solutions Magazine, April 1999, High Mountain Press.)

Figure 1 – The Cost of Change

The most startling statistic relative to design/engineering changes is not the exponential cost curve (Cost vs. Time) but the number of engineering design changes made over time, relative to the milestone events of release-to-manufacturing, and initiation of production. These data, statistically averaged over a large population of product development projects, show clearly that the majority of unnecessary changes are made after the release-to-manufacturing event (Figure 2.) Note that the cycle-time effect of the errors is not reflected in the direct cost analysis above, but follows a similarly exponential pattern across the life cycle of the product development process.

It is clear, therefore, that paying attention to the early detection, preferably *prevention* of unnecessary design changes will have a dramatic effect on cycle time and cost.

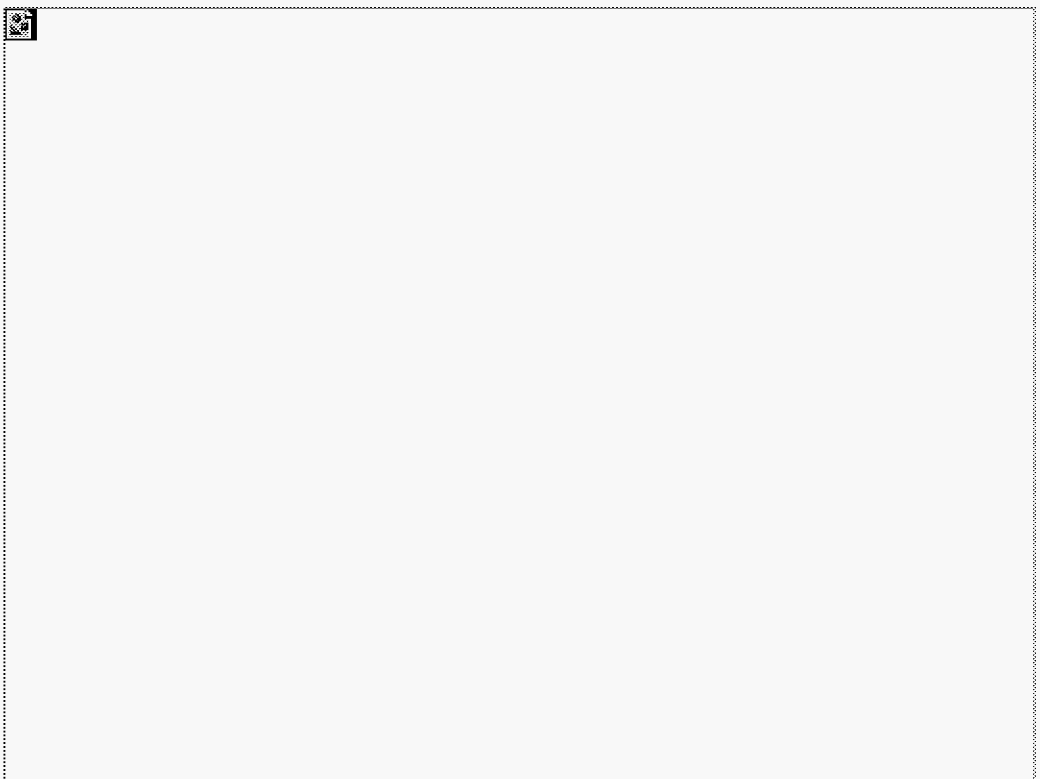

Figure 2 – Number of Changes as a Function of Time

Six Sigma Overview

The Six Sigma quality assurance methodology has several important steps: (Mikel Harry, *Six Sigma Producibility Analysis and Process Characterization.)*

Figure 3 – Steps in the Six Sigma Process

Figure 4 – Additional Step in the Six Sigma Process

Further refinement of this process over time has yielded an additional step, prior to the above step #1, which is known as the "Define" step. In this phase, the specific characteristics of the process are detailed, and the CTQ's are identified in detail. The "Measure" step then is transformed into the part of the process in which measurements are taken. As, such the Six Sigma process has evolved into the process defined in Figure 4.

Sigma Level - Quality Factor

The Greek letter sigma (σ) is a term used to measure how much a process varies from the desired level (perfection.) How then does one create a meaningful measurement system, and what is the process for translating that into a quality factor or sigma level?

The first action is to identify the CTQ's, as described above. Second, every step in the process in which an error (or defect) could occur in a CTQ is identified. The identification of each of these steps creates a quantified metric describing the number of*opportunities* for defects.

The third step is to count the *actual* defects, errors, or failures with respect to CTQ's in the entire process. This defect count is then converted from an absolute error count to a number of defects per million opportunities (dpmo.)

Arriving at the quality factor, or sigma level, is a simple as a table look-up. By comparing the actual dpmo to the appropriate value in the commonly used Table 1 below, the relevant sigma level is obtained.

Number of Defects per Million Opportunities (dpmo)	
690,000	1
308,000	2
66,800	3
6,210	4
233	5
3.4	6

Table 1: Sigma Level Conversion

Six Sigma and The Engineering Product.

The Six Sigma approach applies statistical analysis to the measurement of product characteristics relative to specifications. It results in a set of measures that both quantitatively and qualitatively determine the "goodness" of a process. It is always the case that by measuring the end products, one can obtain a sense of how well the process for making those products is working. This is also the case for the*engineering product*, namely the digital product model.

In point of fact, the digital product model has many of the characteristics of the end product, particularly with respect to the geometric representation of the model. Of course, the non-geometric properties of the physical product must be represented in some symbolic form in the digital version of the product. For example, a dimension (e.g. diameter of a hole) will be equivalently represented in the digital model as it would in the physical part. Material properties might be represented symbolically in the model, as attributes, parameters, or even functions (formulae) whereas in the physical part, these characteristics are inherent in the tangible qualities of the object. So, in order to measure the hardness of a piece of material, one uses techniques in the "real" world that would test the physical attributes. In the "virtual" world, simply examining the value of the "hardness" parameter or attribute would represent the equivalent test.

This brings us to an important issue in the application of Six Sigma to the engineering product. In the manufacturing world it is the operations involved in making the product that provide the opportunity for errors. Similarly, in engineering design, the operations involved in making the digital product provide opportunities for errors, and it is these operations that must be identified and measured. Simply examining the digital product without an understanding of the methods used to create the model will result in an incomplete, even distorted statistical analysis and almost assuredly inaccurate view of the quality of the model and the process.

Essentially, Six Sigma allows for the characterization of quality from the perspective of amount of actual errors with respect to the number of opportunities for making such errors. This statistic is then cast in the form of a number of defects per million. By using a statistical reference to the standard deviations from the average, assuming a "normal" distribution, it is axiomatic that the further away from the average one moves, the defect rate diminishes at an exponential rate. Thus, processes that fall within the 1σ range (sigma, being represented by the Greek symbol "σ ") have more errors than a process that falls within the 3σ range. This is a very useful measuring technique, because it places in context the meaning of the words "average " and "standard deviation." To have a process that is within three standard deviations from the mean (which sounds as if that might be a very well controlled and high quality process) means that there is essentially a 99.73% conformance. While this percentage sounds high, what Six Sigma has done for the quality measurement paradigm is to restate quality from terms of percentages (defects per hundred) to defects per million. Why is this necessary? To begin with, it allows for a discussion of quality in terms of *very* low error rates, which is obviously better than a higher error rates. Second, and most importantly, it frames the context of quality to a meaningful frame of reference for high volume operations. It is not practically acceptable for 0.27% of commercial airline flights to crash, for example. That would translate to 2,700 crashes out of every 1,000,000 flights! Clearly, 3σ quality is unacceptable for the commercial aviation industry.

It is equally unacceptable in today's competitive manufacturing industries to have 2.7 errors per 1000 opportunity. However, most companies do not even yield that level of quality. When framed in the context of parts per million, quality statistics take on a very new meaning, and become a powerful tool for identifying necessary process improvements.

The nature of normal statistical distribution is such that for a Six Sigma (6σ) process, the defect rate would go from 2700 parts per million (0.27%) to 2 parts per *billion*, or 0.002 parts per million. (Figure 5.) In the *parlance* of Six Sigma, a 1.5 sigma shift has been made to allow for a shift in the process mean, so that the commonly accepted dpmo for a 6σ process is now accepted at 3.4, rather than 0.002. From this analysis, it is clear that a tremendous benefit is derived from moving from even a 3σ to a 6σ process!

Figure 5 – Six Sigma Distributions (Source – The Complete Guide to CQA *by Thomas Pyzdek, 1996. Tucson: Quality Publishing, Inc.*)

Characteristics of the Engineering Product

In order to create a statistical analysis of the engineering product population, the dimensions of that analysis must be defined. As such, an examination of the form of the engineering product is required.

a. Geometric Features

One of the primary identifiable elements of a digital model is the geometric representation of the physical object. This representation comprises a set of geometric features, at either a lower-level mathematical basis, or on a higher-level symbolic framework. For either of these types of representations, a quantifiable set of measurable characteristics of the geometry can be identified, and measured.

For example, a lower-level mathematical representation might be a boundary surface, which has a set of edges, and a set of faces defined as "patches" that are developed by polynomial equations that define their shape. One can quantify the number of edges, and the polynomial degree of complexity of the shape definition. A simplistic view of the quantification of operations might be the product of the sum of the edges on each face on each surface, matched against the boundary of each face on the surface. (It is possible that edges are not exactly coincident with the face boundaries, and that misalignment would represent an "error" or defect in the surface definition.)

In a more general description, for each geometric element (curves, surfaces, etc.) a discrete number of operations is required to create the element, and each one of these operations can be considered to be an opportunity for error.

For the more symbolic representations of features, a collection of both geometric and dimensional elements are grouped to form logical sets of basic mathematical entities that together form a more meaningful feature representation. For example, a "hole" feature would consist of a set of surfaces, as well as some other basic mathematical entities, and would be described by its location ([x;y;z] position of its origin) its radius (r), and its length (l). (Figure 6.) In many cases, these feature types have been grouped specifically to match physical feature descriptions, so that a hole feature in a digital product would be equivalent to the hole in the real part. For each of the basic references of the feature's definition (position, radius, and length, for example) an operation is needed and this is, therefore, measurable as an opportunity for an error.

Figure 6 – Geometric Feature: Type=Hole

- Non-Geometric Attributes

As was described above, in a digital model, non-geometric entities are generally represented as attributes, or parameters. These may be one of any number of basic types, including strings, integers, floating numbers, date/time, or lists and combinations of the above basic types. These attributes range from simple (single type-value pairs) to complex (classes and instances of groups of type-value pairs.)

At the basic element level, an opportunity for error would be defined as any required field in the attribute