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An Analysis of Step, Jt, and Pdf Format Translation Between Constraint-based Cad Systems with a Benchmark Model

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ABSTRACT

McKenzie-Veal, Dillon. M.S. Purdue University, May, 2012. An Analysis of Step, Jt, and Pdf Format Translation Between Constraint-based Cad Systems with a Benchmark Model. Major Professor: Dr. Nathan Hartman.

This research was conducted to provide greater depth into the ability of STEP AP 203 Edition 2, JT, and 3D PDF to translate and preserve information while using a benchmark model. The benchmark model was designed based on four industry models and created natively in the five industry leading 3D CAD programs. The native CAD program models were translated using STEP, JT, and 3D PDF. Several criteria were analyzed along the paths of translation from one disparate CAD program to another. Along with the analysis of the three interoperable file formats a survey was conducted to determine how well the benchmark model captures what is used in industry and whether a benchmark model could be used for an industry or company. Several industry experts participated in the survey to determine what important criteria does a potential benchmark model need to capture. The conclusions of the research show that neither interoperable file format out-performs the other for a majority of the analysis criteria. The survey suggests that a benchmark model could be used in an industry or company and the general structure of this benchmark.

CHAPTER 1 INTRODUCTION

1.1. Background

Today's economy is more global than ever. In the past 10 years the way companies communicate has changed dramatically. Companies are sending most, if not all information digitally instead of by paper. No longer do companies have to print thousands of pages of paper to send halfway around the world to another company. One company can send the product info by way of the internet, or mail digital media to another company. Another way to save time and money is the business mindset of Product Lifecycle Management (PLM).

"PLM is a strategic business approach for the effective creation, management, and use of corporate intellectual capital, from a product's initial conception to its retirement, aimed at streamlining product development and boosting innovation in manufacturing" (Amann, 2002; Sudarson, 2005). In order to properly follow through with the PLM concept, all the software that a company has, particularly the CAD systems, have to be able to communicate with each other and be interoperable.

"Interoperability is the ability to communicate product data across different production activities" (Brunnermeier, 1999, p. ES-1). CAD interoperability is the ability for disparate CAD systems to communicate with each other, as well as other computer aided software systems used in various design processes. This is very important since there are many CAD software systems and computer aided technologies being used in many industries.

> Data exchange among CAx systems has been recognized for a long time as a key concept for concurrent engineering which tries to coordinate product development processes involved designers from different departments in the same company, as well as from different enterprises. (Valilai, 2010, p. 2)

“[Interoperability] is essential to the productivity and competitiveness of many industries because efficient design and manufacturing require the coordination of many different participants and processes that rely on a digital representation of the product” (Brunnermeier, 1999, p. ES-1). Interoperability causes problems in the design process leading to significant economic inefficiencies at an estimated cost of $1 billion in the U.S. automotive industry during 1999. These interoperability costs are predominantly due to supporting multiple CAD/CAx systems and fixing errors when data is exchanged between desperate software systems. (Brunnermeier, 1999, p. 5-1).

To help solve the problem of interoperability an international standard was created, ISO 10303, also known as STEP. “STEP (STandard for the Exchange of Product Model Data) is an international standard addressing the representation and exchange of product data” (Ball, 2008, p. 223). STEP AP 203 edition 2 is the most common of the many STEP application protocols (AP) and most widely implemented by CAD vendors.

STEP has been around for more than a decade but still has significant problems such as the resulting file is difficult to adapt, often a dumb solid, and the construction history is missing (Ball, 2008; Pratt, Anderson, & Ranger, 2005). As a result, it appears as if some file formats have been created to try to become a more comprehensive CAD interoperability file format. Some of these file formats are 3D PDF, developed by Adobe, and JT, developed by Siemens. With what looks like many file formats trying to solve the interoperability problem, it could be very useful to people in small businesses who use these file formats but may not have the capitol for expensive translation software and industries who use CAD tools to know the detailed interaction of CAD software and the file formats.

1.2. Research Question

How do STEP AP203 edition 2, JT, 3D PDF, and constraint-based native CAD file formats’ capabilities compare to each other with regards to preservation of information?

1.3. Significance

Every industry that uses CAD software must address problems that stem from limited file mobility due to the lack of robustness of interoperable file formats relative to native formats. Every day the world becomes more connected and able to more easily transfer almost any type of media. Companies have been outsourcing work for years and there seems to be no decrease. “The potential for STEP is in the lower tiers of the supply chain, where the typical company does not have the resources to support multiple complex systems to meet the needs of different customers” (Gallaher, 2002, p. 59). The potential seen in STEP could also be generalized to apply to any interoperable file format.

Many small to medium size companies or SMEs, less than 500 employees, have customers who are larger OEMs who can keep up with current technology and have the resources and capitol to spend on extra software to maintain various CAD systems. Small to medium size companies do not necessarily have the capital or man power to invest in new software and the problems anything new can bring (Wickramansinghe & Sharma, 2005). Problems can also arise inside a company if they have multiple CAD packages. Interoperable file formats need to become more robust with help from outside the CAD industry. Better interoperability due to better interoperable file formats will result in a better product in less time and with less money (Gerbino, 2003).

Companies moving towards concurrent engineering need to be able to have CAD software work together if they are using disparate systems. Model quality can be critical before and after the model leaves its native program. If an error occurs in the model quality downstream, determining the source of the error can be difficult. Data integrity is crucial to successful interoperability (Gu, Chase, Cheney, Baily, & Johnson, 2001). Knowing what the error is, and the common causes, can save a company time and money. This is especially true for SMEs who may not have the capital to have an expert on staff, hire a consultant, or to purchase expensive aftermarket analytical software. In 2003, International TechneGroup Incorporated (ITI) found that up to 70% of a person’s time can be spent correcting interoperability errors when performing engineering analysis on a model downstream. An in-depth study of what errors occur and if there is a trend related to the file format or CAD software could prove very beneficial to many companies, especially SMEs.

Numerous engineering CAD programs are available on the market today. Companies often use multiple CAD programs in-house or work with other companies who have different CAD programs. There exists no in-depth, multilevel comparison of the interoperable file formats and various individual proprietary CAD packages. This research paper could answer how CATIA V5, NX7, Pro/E, SolidWorks, and Autodesk Inventor’s reading/writing ability of interoperable file formats compare to each other. In order to properly assess the capabilities of each CAD program, a benchmark model needs to be used. This research will help answer what comprises a benchmark CAD model with the complexities and integrated product definition data needed to accurately represent today’s sophisticated products. To better understand the capabilities of each CAD program, the capabilities and limitations of the interoperable file formats being used must be understood.

1.4. Scope of Project

This research will focus on analyzing how certain constraint-based CAD systems implement different file formats, and comparing those file formats capabilities and limitations to each other. The research will be comprised of three sections.

The first section will be obtaining an industry CAD model for each of the five CAD systems, specifying a benchmark model from the industry models, and then creating the benchmark model natively in the five CAD systems. The industry models will not be modified in any way. The benchmark model will be created to the determined specifications in each of the five CAD systems. The benchmark model will be made in as similar a process as possible even though each CAD system could represent or construct geometry in a different manner.

The second section will involve the analysis of the three interoperable file formats STEP, JT, and 3D PDF, along with five CAD system file formats. The industry models and the benchmark model will be translated, natively and by way of the three file formats, between the five CAD systems and will be documented and discussed.

Similarities and differences of how the CAD systems import and export all of the different file formats noted and discussed.

The third section of this research will involve a survey of experts inquiring about their qualitative opinion on how the BM compares to industry grade models, with regard to assembly complexity, geometric complexity, and GD&T among other evaluation criteria. Several industry experts in various fields involving, CAD software and design will respond to questions about the benchmark model.

1.5. Assumptions

This research is conducted and the results are analyzed under the following assumptions:

- Each CAD program's native benchmark model will not be the exact same as other native CAD programs' benchmark model due to the differences of how each CAD program functions at the kernel level and how each program represents construction geometry.
- Each of the CAD software developers have different conversion processes from their native file format to the interoperable file format based on the developer's interpretation of the interoperable file format.
- Any differences in the interoperable file formats of each model are based on the corresponding CAD software the model was translated from and not on how any of the individual interoperable file formats handle the model at the code level.

1.6. Limitations

The limitations for this research include:

- The third party CAD validation tool used is limited to ITI TranscenData's CADIQ v7.0.0i16 because of availability and its capacity to analyze native file formats.
- ITI TranscenData's CADIQ cannot read native Autodesk Inventor 2012 or 3D PDF files, and will therefore use the STEP format for analyses.
- The process for creating the benchmark model will be the same for each CAD program as much as possible being limited by each CAD program's functionality.

Therefore, the benchmark models for each CAD system will vary in how some features are made but the resulting models will be as close as possible.

- Not all of the CAD systems being used can translate their specific native file format directly into a different native CAD file format or some of the interoperable file formats. As a result, some CAD systems will be unable to be analyzed in this aspect.
- SolidWorks 2010 is used because it was the only version available, even though newer versions were available at the time of the testing.

1.7. Delimitations

The delimitations for this research include:

- Three-dimensional constraint-based solid modeling will be used in this research.
- CAD modeling processes and techniques will not be compared or evaluated in this research because of the variation in them when used in constraint-based modeling programs.
- Surface modeling will not be used in the process of creating models.
- The only non-native file formats being used and tested are:
    - STEP AP203 edition 2 (part of ISO 10303).
    - JT 9.5:
        - Representation:
            - B-Rep.
            - XT B-Rep.
            - Facets
            - B-rep and Facets
        - File Structure:
            - Fully Shattered
            - Mimic
            - Monolithic
            - Per Part

  - 3D PDF with PRC.
- The only native CAD file formats being used and tested belong to the CAD software:
  - CATIA V5
    - *.CATPart
    - *.CATProduct
  - NX 7.5
    - *.prt
  - Pro/Engineer 5.0
    - *.prt
    - *.asm
  - Inventor 2012
    - *.ipt
    - *.iam
  - SolidWorks 2010
    - *.sldprt
    - *.sldasm
- The only CAD software being used and tested is:
  - CATIA V5 R20.
  - NX 7.5.0.32.
  - Pro/E 5.0.
  - Autodesk Inventor 2012 SP1
  - SolidWorks 2010 (SP5.0).
- The third party software being used for testing is:
  - Adobe Acrobat X with the Tetra 4D add-on
  - ITI TranscenData’s CADIQ v7.0.0i16
- The computers or any third party background software’s performance is not considered as a variant for any of the results that could be affected as a consequence of said performance.

1.8. Definitions of Key Terms and Abbreviations

3D PDF – (PDF/E) a file format created by Adobe based on the PDF format that provides native support for 3D data and manipulation (ProSTEP AG, 2011).

AI – is used as an abbreviation for Autodesk Inventor within this research paper.

Analytic Geometry – “The analysis of geometry structures and properties, principally using algebraic operations and position coordinates. The term also refers to a particular geometry method for describing 3D solid models” (Bertoline & Wiebe, 2007, p. G-1).

AP – Application Protocol. “A set of rules and formats (semantic and syntactic) that determines the communication behavior of application entities in the performance of application functions” (ATIS, 2007).

BM – Benchmark Model prototype created for this research.

BMs – Plural form of BM. More than one benchmark model.

CA – is used as an abbreviation for CATIA V5 within this research paper.

CAD – Computer Aided Design.

CATIA – Specifically referring to CATIA V5. A 3D CAD/CAM/CAE software suite developed by Dassault Systèmes.

CAx – Computer Aided technologies.

Constraint-based Modeling – Also known as history based modeling. It is 3D CAD Modeling using a feature history tree, parameters, and relationships that capture design intent. When changes need to be made, parameters are modified and the rest of the model updates itself based on the feature history tree (Gordon, 2006).

Control Points – ”Points used in conjunction with spline curves. These points are not part of the curve proper, but the relationship between the control points and the points on the curve is used to define the shape of the curve” (Bertoline & Wiebe, 2007, p. G-5).

EXPRESS –The formal specification language used by STEP to specify the product information to be represented (SCRA, 2006).

IM – Industry Model. Refers to a model(s) obtained from the industry.

Inventor – A 3D mechanical design software developed by Autodesk.

JT – Jupiter Tessellation; "JT format is an industry focused, high-performance, lightweight, flexible file format for capturing and repurposing 3D Product Definition data that enables collaboration, validation and visualization throughout the extended enterprise" (Siemens, 2010, p. 13). It is used as an abbreviation for the JT file format within this research paper.

NIST - National Institute of Standards and Technology.

NX or *NX7.5* – A 3D CAD/CAM/CAE software developed by Siemens. (# stands for the version).

PDF – is used as an abbreviation for 3D PDF within this research paper.

PDM – Product Data Management.

PE – is used as an abbreviation for the Pro/E CAD program within this research paper.

PLM – Product Lifecycle Management.

Pro/E – Pro/ENGINEER; a 3D CAD/CAM/CAE software solution developed by PTC.

SME – Small and medium enterprises. "A unique definition of SMEs is not possible, the concept varies from country to country and from sector to sector. However, in terms of the structural funds and leading instruments of the EU, it has always been accepted that the SME should not have a workforce exceeding 500, or net fixed assets of more than a third of the capital held by a large firm" (Marri et al., 1998, p. 936).

SW – is used as an abbreviation for the SolidWorks CAD program within this research paper.

SolidWorks – A 3D mechanical CAD program developed by Dassault Systèmes.

ST – is used as an abbreviation for STEP AP 203 edition 2 within this research paper.

STEP – "the Standard for the Exchange of Product Model Data is a comprehensive ISO standard (ISO 10303) that describes how to represent and exchange digital product information." (http://www.steptools.com/library/standard/)

1.9. Nomenclature

Throughout this research paper specific nomenclature will be used to describe a translation path and/or a model. For example, a model, when not described with full names, could be described using CA_BM, CA2ST, or CA to ST. CA_BM means CATIA V5 benchmark model. CA2ST means the STEP model that was translated from CATIA V5; so it represents what the model is and where it came from. CA to ST is the same as CA2ST just less concise and more formal. Two letter abbreviations are used throughout this research paper and their explanation can be found in the section above, Section 1.8.

1.10. Chapter Summary

This chapter provided the scope and significance of the research in this thesis. The research question provided the basis for the research along with the assumptions, limitations and delimitations.

CHAPTER 2 LITERATURE REVIEW

This chapter provides an overview of significant literature regarding the research in this study. PLM and interoperability in general are discussed. Literature regarding the STEP standard, JT file format, and the 3D PDF file format is discussed. Most importantly a review of previous studies containing STEP, JT, 3D PDF and other interoperable file formats is included.

2.1. Introduction

Today's economy is more global than ever. Companies are outsourcing and in the past 10 years the way companies communicate has changed dramatically. Companies are sending most, if not all information digitally instead of by paper. This can be considered a great leap forward in saving time and money. No longer do companies have to print thousands of pages of paper to send halfway around the world to another company. The receiving company does not have to take those paper prints and recreate them exactly in a CAD system. One company can send the product info by way of the internet or mail digital media to another company. Another way to save time and money is the business mind set of Product Lifecycle Management (PLM).

2.2. Product Lifecycle Management

A business mindset that can help with this is PLM. "PLM is a strategic business approach for the effective creation, management and use of corporate intellectual capital, from a product's initial conception to its retirement, aimed at streamlining product development and boosting innovation in manufacturing" (Amann, 2002; Sudarson, 2005). Companies want to be able to keep data with a product from concept to retirement of the product. In order to properly follow through with the PLM concept, all the software that a company has, particularly the CAD systems, have to be able to communicate with each other. This is not a problem when a company only has one CAD system. However, if company A does work for company B that has a different CAD system then it can become a problem. For PLM to be successful, data formats must be able to convey design intent, be machine interpretable, and lose as little information as possible in the translation process. From a Kubotek USA study in 2006, some examples of the problems that can arise within companies having different file formats and companies outsourcing are:

- Fifty percent of some companies have to redesign an object, based on current data or on 3D data they received, as frequently as once a week and sometimes more often.
- Eighty-four percent of those people who use a history-based modeling tool resort to editing the original feature trees within the CAD model.
- Forty-three percent of those surveyed said they used the CAD system that the model was made in to make changes to the object.
- On a monthly basis, 44 percent of respondents said they send or receive CAD files in a format that is not the same as their preferred system.
- On a monthly basis, 37 percent of those surveyed send or receive four or more CAD files in a format that is not from their preferred CAD system.

PLM implementation can be a long and expensive process. Companies usually do not see returns from PLM for several years. However, the long term gain can heavily outweigh the short term upfront cost. Having interoperability issues can only add to the time and money up front and delay those long term gains.

The major issue at hand is that of interoperability between CAD systems. Companies can have issues even in-house if multiple CAD systems are used. Companies want to be able to implement PLM software because of the long term benefits it has. Another issue can arise when companies do not want to give away intellectual property. A company will want to be able to share just enough information but not give away anything else, even when the same CAD systems are used.

2.3. Interoperability

"Interoperability is the ability to communicate product data across different production activities" (Brunnermeier, 1999, p. ES-1). CAD interoperability is the ability for disparate CAD systems to communicate with each other, as well as other computer aided software systems used in various design processes. This is very important since there are many CAD software systems and computer aided technologies being used in many industries.

> Data exchange among CAx systems has been recognized for a long time as a key concept for concurrent engineering which tries to coordinate product development processes involved designers from different departments in the same company, as well as from different enterprises. (Valilai, 2010, p. 2)

"[Interoperability] is essential to the productivity and competitiveness of many industries because efficient design and manufacturing require the coordination of many different participants and processes that rely on a digital representation of the product" (Brunnermeier, 1999, p. ES-1). Interoperability causes problems in the design process leading to significant economic inefficiencies at an estimated cost of $1 billion in the U.S. automotive industry during 1999. These interoperability costs are predominantly due to supporting multiple CAD/CAx systems and fixing errors in when data is exchanged between desperate software systems. (Brunnermeier, 1999, p. 5-1).

Different CAD systems generally have different ways of representing a CAD model, which is determined by the system's modeling kernel. Some CAD systems use the same modeling kernel as other systems. For example, some of the shared modeling kernels are ACIS by Spatial Technology Corporation and Parasolid by UGS. Other companies use completely proprietary modeling kernels that are not shared. The modeling kernel determines how the CAD model is mathematically represented, semantically represented, and the internal accuracy of the geometric definitions (Gerbino, 2003). Some common problems that occur with failed interoperability are (Gallaher, 2002):

- Recreating the model from start in the new CAD program.
- Repeating the conversion process.

- Recreating missing, collapsed, or inverted faces of a model.
- Models that do not form closed solids (surfaces and edges do not connect).
- Models with incorrect feature orientation.

At high costs, companies sustain numerous CAD systems, fix models that are converted incorrectly, manually recreate any data not able to be translated, and discard any models beyond repair because of inadequate interoperability (Gallaher, 2002). Interoperable and standard file formats were created to help with interoperability.

2.4. Interoperability Related Errors

Companies moving towards concurrent engineering need to be able to have CAD software work together if they are using disparate systems. Model quality can be critical before and after the model leaves it’s native program. If an error occurs in the model quality downstream determining the source of the error can be difficult. Data integrity is crucial to successful interoperability (Gu et Al., 2001). Knowing what the error is and the common causes can save a company time and money. This is especially true for SMEs who may not have the capital to have an expert on staff or the ability to purchase expensive aftermarket analytical software.

Model errors can be categorized into topology and geometry errors (Gu, 2001; Yang, 2005; ITI, 2003). Topology errors can be divided into structure and accuracy errors. Geometry errors are often called realism errors (Gu, 2001; ITI, 2003). Structure errors occur when topological elements like vertices or a face of a model are not defined or incorrectly linked. “Structural problems include loop orientation inconsistencies, missing geometry and self-intersecting geometry among others” (ITI, 2003, p. 3). Structure errors most often cause the model to be an invalid solid. Some CAD systems will not allow the user to continue until the error is corrected. An invalid solid can cause many problems downstream in the concurrent engineering process (Gu, 2001).

> An example of a structural error is a face with an edge that isn't shared by another face. In a manifold solid volume, such edges should not exist because they cannot physically be manufactured. They occur because some solid modeling programs allow non-manifold topology as a midpoint to creating complete

> volumes. If these errors are not fixed, manufacturing and analysis programs will reject the models. (ITI, 2003, p. 4)

Accuracy errors occur when gaps between geometric entities are too large. Accuracy requirements defined by the user in CAD software place limits on gaps between geometric entities and can limit the minimum size of trimmed entities (ITI, 2003). If the gap is large enough, the CAD software may not define the model as a solid. This can cause problems in the CAD software and downstream applications that use meshing and define tool paths.

Realism errors are geometry errors and not topological. Many times a model is defined as a solid, while realism errors could still be present. Most often, realism errors are unintended artifacts from combing solid features (Gu, 2001). Realism errors are often invisible and consist of transition cracks and sliver faces (Gu, 2001; ITI, 2003). Depending on the application the user can determine if these types of errors are allowable.

There are many studies defining what CAD modeling errors are and how to find them. No papers have been found that relate the defined errors to specific CAD file formats and what errors occur during the translation process between different CAD software using various file formats.

2.5. The STEP Standard

The issue of interoperability and proprietary information has brought about interoperable and lightweight file formats into existence. The most well-known interoperable file format is ISO 10303. The most widely implemented and used ISO 10303 standards are AP203 edition 2 and AP214. "STEP (STandard for the Exchange of Product Model Data) is an international standard addressing the representation and exchange of product data" (Ball, 2008, p. 223). Even though STEP has been around for more than a decade, it still has significant problems, "the original designer's intent may be lost or misunderstood, the exchanged model is difficult to modify, and the construction history of the design is lost" (Ball, 2008, p. 223). This is clearly evident from the problems explained previously. When using STEP, significant data loss can occur. Large companies either buy expensive third party software solutions or design them in-house. Even then, a STEP representation of a file may not be exactly the same as the original native file. It is beneficial and sometimes legally required for companies to keep every bit of data that has been made on a product for many years, if not forever. STEP is also not advantageous for storing data long term. Storing data long term is a large part of the PLM process.

STEP and any other standard must deal with many problems in industry. One of these problems is that vendors must develop a way to read and convert to standards they choose appropriate. Sometimes this requires a lot of invested time and money to stay standard compliant. This can be difficult for companies to justify when they could be indirectly promoting competitors' products by staying standard compliant. Initial effort into making STEP work for a company can be high risk and high cost, especially if they utilize outside help. Once the company has everything worked out, their competitors will eventually get access to the same technology with much less risk and maybe less cost, especially for large businesses. This leaves no incentive for small or medium sized companies to invest time and money into making a standard work for them.

Another problem that arises is the legal aspect. Most of the legal processes today assume the use of paper. Electronic documents sometimes "cannot be interpreted without adequate software, are less accessible for a judge, and therefore less suited as evidence. Furthermore, electronic 'evidence' is easy to falsify; its originality must therefore be proven" (Gielingh, 2008, p. 752).

2.6. Interoperable Lightweight File Formats

"The STEP standard is generally considered as superior to other standards for geometric data exchange, but it appears that errors cannot be fully avoided. Anomalies in the exchange differ from CA-application to CA-application, and from translator to translator" (Gielingh, 2008, p. 753). This could partially be due to the fact that different venders take different approaches to exporting a STEP file, such as schema implementation and available export options. Because of the pitfalls of STEP and no current action being taken to fix them, lightweight file formats have come into existence.

There are over 10 different types of lightweight file formats that have been specifically designed to do some aspect of CAD translation really well.

Even the newer lightweight file formats have problems. Like STEP "there is no one lightweight format that stands out as ideal in all scenarios" (Ball, 2007, p. 6). "With the proliferation of emerging visualization formats, confusion exists in industry with regard to the use of these formats relative to STEP and other standard data formats" (Hartman, 2009, p. 39). How is a company to know what they should use without major risk by way of investment into a particular technology? No software vendor or technological society will explain what shortcomings their particular software or file format has.

In order for a company to make a decision on a standard or CAD software, it would be very advantageous of them to know all the facts. There currently exists no industry-wide assessment of the most predominantly used interoperable file formats: 3D PDF, JT, and STEP. A private company could have done this already; however, this information could give them a competitive edge over other companies, therefore very little information if any is made available outside the company. It is important to have an industry-wide assessment because it helps the small and medium sized businesses figure out what standards and what CAD software they are going to use. This goes back to small and medium sized businesses not wanting to take investment risks. If they knew all the facts, or more facts than are currently available, they would be more likely to take a risk that would not end in financial loss.

2.7. Previous Studies on Interoperable File Formats

Previous research has been performed to determine the differences of STEP and lightweight file formats. However, the last major STEP comparison of any kind was in 1999 by the Research Triangle Institute for the National Institute of Standards and Technology. This study simply analyzed the transfer of models from one CAD package to another by way of STEP and an outdated standard, IGES (Brunnermeier, 1999). This study was very simple and maybe effective for 1999, but technology, the standard, and other variables have improved and changed since then.

There have been more recent studies performed on lightweight file formats like Lightweight Formats for Product Model Data Exchange and Preservation by Ball, et al., 2007. However, this study only covers the basics of “model fidelity, metadata support, security features, file size, software support, and openness” (Ball, 2007, p. 2). These aspects are important to know for any company. Studies like this are also important to state the inherent differences in the lightweight file formats, promoting further improvement in them if they want to successfully compete. However, this study simply compares the basics of lightweight file formats against each other and does not include the most widely used and well-known standard, STEP. Often a company wants a more in-depth comparison that involves major CAD systems, if they are going to invest any significant amount of time and money.

Companies and academia have performed studies to try and evaluate where STEP falls short. The last most comprehensive study on STEP was by Clark, et al., in 1995, STEP AP203 Data Exchange Study. This study fell short in its analysis, which was stated in the published report:

- STEP translators need more testing and development
- STEP validation tools needed
- Rigorous test protocol needed
- Rigorous error analysis needed
- Database and process control support software needed

Some of these shortcomings still hold true even after 15 years. The STEP translators have had more testing, time to develop, and have even improved. However, all of the information that has been produced from testing is all proprietary and the companies performing the testing are those making the software. These companies are not going to release the results generated from testing. It is the same issue with STEP validation tools. STEP validation tools now exist but no in-depth data about these STEP validation tools exists publically. Again, rigorous test protocol and error analysis probably exists within the companies that make their corresponding software, but not publically. The lightweight file format studies that exist publically only give general details and conclusions.

ProSTEP iViP Association is an international association that helps drive the development of vendor-neutral file standards and validates the quality of software solutions for interoperability. ProSTEP performs research on benchmarking STEP and JT. ProSTEP published *3D Formats in the Field of Engineering - a Comparison* in 2010, in which JT, STEP, and 3D PDF were analyzed using multiple CAD systems and several attributes. The CAD systems used were CATIA V5, Pro/Engineer, and Seimens NX. The interoperable file "formats were examined to determine the extent to which their attributes are suited to five use cases that are most frequently found in companies" (ProSTEP AG, 2011). The five cases used were: viewing engineering data, data exchange, digital mock-up (DMU), documentation and archiving, and use in the portable PLM document. Within each of the use cases, criteria is used to determine which file format is best for each case. The criteria used in the research include the availability of free viewers for a given format and the features the viewer's offer, available software and converters, software development kits for the individual format, the level of compression that can be achieved and file size, and standardization aspects (ProSTEP AG, 2011). ProSTEP has also performed in-depth studies focusing exclusively on STEP.

The studies ProSTEP has performed on STEP AP214, not on AP203, with multiple CAD systems validated the volume, surface, center of gravity, the completeness of the geometry transfer for solids, the structure of an assembly, and the corresponding names of parts. ProSTEP also notes model transfers that deviate from the original, volume could not be calculated, only the surfaces transferred resulting in no solid model, and models that crashed during a transfer. The complete methodology and detailed results are only provided to the members of ProSTEP. Similar studies have been conducted with more detailed results provided by CAx-IF.

CAx Implementor Forum (CAx-IF) is a closed group of software developers and testers, composed of CAD vendors and second or third party software companies. All persons involved must sign a non-disclosure agreement and the test models are treated confidentially. Results are not made public but problems found with STEP are broadly defined and guidelines to help with these problems are published in different recommended practice papers for specific functionalities. The complex models used in testing are often not made public, and if they are, only a picture of the model. The different functions of STEP CAx-IF has tested include:

- Geometric validation properties (e.g. centroid, volume, and surface area)
- Assembly validation properties
- Applied material, mass, and density
- GD&T: representation and presentation
- PMI (e.g. cutting planes, center lines, tool targets)

No data or specific evaluation criteria related to any of the software used in testing has been made publically available. CAx-IF only tests STEP and no other file formats.

The lightweight file format studies that exist publically do not go into enough detail and comparison. An example of test measures that have been used in a lightweight file format comparison, Testing Semantic Interoperability, by Ma, et al. (2006):

- File size
- Differing numbers of instances
- Inconsistent object types
- Inconsistent attribute values
- Schema inconsistencies

The testing was done on translators alone ,only comparing the input to the output. This sort of testing only looks at the small picture, therefore a study needs to be done to look at the big picture. Everything from the lightweight file formats to the CAD packages available need to be examined and compared. This sort of study needs to be done all at once to help determine if companies follow the STEP standards and if not, where do they fall short.

Software companies most often do not follow even the international STEP standard completely. They have their own interpretation of the standard. The interpretation is what they use to code their translators (Gerbino, 2003). The reason for allowing an incomplete translation is to keep people from using other CAD software. “Leading [CAD] vendors benefit from a situation where suppliers are obliged to use the same [CAD] system as their clients, usually OEM’s, to facilitate an error-free exchange of product data" (Gielingh, 2008, p. 752). Vendors who offer suites of CAD software that natively work together will not invest in something that makes its competitor's products a more viable option (Gielingh, 2008). This forces the companies that use their software to use the whole suite or only do work with companies that have the same software. Because of this, third party translators have come about with some that do direct native file format to native file format. Others are more complete file translation from a native file format to a standard. Companies taking a large risk in investing in some of this technology should know exactly what it can and cannot do. They could ask the vendors who developed and are promoting each particular piece of software, but it is in the company's best interest to not fully disclose its limitations. After all, the vendor is trying to sell something, so they are not going to reveal the shortcomings of their software.

Using SolidWorks and Autodesk Inventor in this research will be helpful and bring new insight into how they interact with other file formats. Previous studies have used CATIA V5, Pro/Engineer, and Siemens NX as the 3D CAD software. One study, performed by ProSTEP iViP in 2003, analyzed only STEP translation using Autodesk Inventor. None of the previous more recent studies found have used SolidWorks or Autodesk Inventor. In a survey performed in 2010, the primary 3D CAD platforms among respondents were SolidWorks, Autodesk Inventor, Pro/Engineer, CATIA V5 and Siemens NX (LongView Advisors, 2010). Also found in the *Collaboration & Interoperability Market Report 2010*, is that the SolidWorks native file format is the second most popular format used by the respondents for 3D data exchange.

It is clear that an in-depth multi-level comparison should be done with the STEP standard and major lightweight file formats. One of those lightweight file formats should be JT. "JT is a widely accepted, system-neutral file format that was developed by Siemens PLM Software" (Eigner, 2010, p. 91). JT is a PAS or Publicly Available Specification. JT provides several advantages over STEP but an in-depth, qualitative study is needed to prove the advantages. 3D PDF would be another widely used lightweight file format. This is because a 3D PDF can be viewed with Adobe's free Acrobat Viewer. Anyone with an up-to-date computer can view and manipulate the model in 3D space. 3D PDF is also a PAS, Publicly Available Specification.

The issue of interoperability may never go away but it can definitely be improved upon by more complete and in-depth studies. Even though different software venders take different approaches, these approaches should be known by anyone considering buying the vender's software. This would give small and medium sized business more incentive to take a calculated risk adopting a piece of software or standard file format.

2.8. Importance of Expertise

The benchmark model (BM) used on this research will be well documented in terms of how it is made and everything the model is composed of. The BM will be based on previous studies and what can be supported as sufficient for this research. The BM is supposed to be a good example of a product a company could produce in industry, allowing for better comparisons to problems that could occur for the company in the product's life cycle. Experts will be used in order to provide outside validation that the BM is a good representation of what any person or company could make or use in industry. Experts will analyze the BM to determine how well the model captures what is occurring in industry in their opinion. However, in order to use experts for validation, potential experts must be identified. First, what makes an expert an expert needs to be determined.

"Expertise refers to the manifestation of skills and understanding resulting from the accumulation of a large body of knowledge" (Chi, 2006, p. 167). One way researchers have conceptualized expertise is centered on knowledge, defining an expert as a person who understand and can apply a great amount about a specified domain. "Knowledge is a necessary condition for expertise" (Sternberg, 2000).

> Expertise may be viewed as an attribute not just of a person but of the way a person is perceived by other persons – as an interaction between a person and a situation. In this case, expertise can been seen as in part a labeling phenomenon whereby some group of people declares a person an expert. Without that declaration, the person may have difficulty in exercising expertise. (Sternberg, 1994a as citied in Sternberg et al., 2000, p. 3)

An expert is a person who has a background in a particular domain, is regarded by his or her peers as an expert, or is determined to be an expert by researchers conducting an experiment regarding that particular domain. When experts are chosen, a person who is knowledgeable and experienced in an area at the level required could be considered an expert (Meyer & Booker, 1991).

Society often differentiates between professions simply based on the degree of qualified knowledge (Weber, 1978). This is usually done when a person has reached a certain level of domain or professional knowledge by being bestowed a degree or certificate. This can lead society to consider "a person…an expert because she is regarded as such by others" (Sternberg & Frensch, 1992, p. 194).

Expertise can be determined by the knowledge a person has attained over time. An expert could be defined as someone who has spent years working on a single domain and who has a degree(s) and certificates based on their work in that specific domain. An expert can be a person who is recognized by their peers as an expert.

2.9. Chapter Summary

This chapter summarized how interoperable file formats play a vital role in PLM. An overview of the STEP standard and other interoperable file formats was discussed. Most importantly, a look at the literature from previous studies on interoperable file formats and where they fell short was included.

CHAPTER 3 METHODOLOGY

This chapter presents the framework and methodology for the research in this thesis. The models being used are presented in the sample set. The software used is presented along with how the results will be analyzed and any possible bias is discussed.

3.1. Computer & Software

All of the testing took place on the same computer to ensure that everything is the consistent for each individual test. The computer used was an HP Z400 Research Computer. The computer had an Intel Xeon W3550; 12.0 GB of RAM; running Microsoft Windows 7 Enterprise x64 bit. All software used was installed and run locally from said computer.

Five different CAD packages were used in this study. These five CAD packages were chosen because their respective companies market share of top CAD vendors. According to the World CAD Marketing Report 2010 by Kathleen Maher of Jon Peddie Research, Autodesk, Dassault, UGS (Siemens), and PTC are the top five CAD companies with the most market share. The five CAD packages are:

- CATIA V5R20 (Dassault Systèmes)
- UGS NX 7.5 (Siemens)
- Pro/ENGINEER Wildfire 5.0 (PTC)
- Autodesk Inventor 2012 (Autodesk)
- SolidWorks 2010 SP5.0 (Dassault Systèmes)

Third party software was used to analyze the completeness of the interoperable file formats and the integrity of all the CAD models, native and neutral. The third party CAD analysis software used was ITI TranscenData’s CADIQ V7.0.0i16. Adobe Acrobat X with the Tetra 4D add-on was used to convert CAD native formats to the 3D PDF format, as well as viewing the subsequent PDF.

The CADIQ CAD validation tool was chosen due to availability of related software, the scope of the research, and how the program evaluates the CAD models. Other CAD validation tools exist, however, CADIQ can analyze the CAD models in their native file format except for Autodesk Inventor.

3.2. Sample Set

The sample set of CAD models was comprised of four native models attained from industry. All of the five CAD programs are represented except for NX. The models obtained from companies in industry have similar complexity and characteristics that were used when making the benchmark model. Each model had to have originated in the CAD program it will be used for in analysis. For example, the CATIA model must have been created in CATIA with no conversion from another CAD program or non-native file format for any part of the model.

3.2.1. Industry CAD Models

The industry CAD models were different models obtained from a company that created the native model native in the corresponding CAD program. The primary purpose of the industry CAD models was to have a foundation on which to build the benchmark model.

3.2.2. Benchmark Model Creation

A benchmark model (BM) was created based on the attributes of the four industry models. The BM was a generic model that attempted to capture all of the attributes the industry models have. The BM was created individually in each of the CAD programs such that it natively exists in each of the CAD programs. This made the testing of the CAD programs and interoperable file formats as identical as possible such that comparisons were analyzed at a much greater detail than with dissimilar CAD models.

Criteria the benchmark model had based on the industry models:

- Assembly of multiple parts.
- Sub-assembly/assemblies
- Number of parts
    - Number of unique parts
- Number of Standard Parts
    - Number of unique standard parts
- Detailed feature tree (renamed features specifically for that part)
- PMI
    - GD&T
    - Picture, Polyline, or integrated
    - Special PMI characters, i.e. center line
    - Various fonts
- Applied material with corresponding colors and material properties.

3.3. Data Analysis

Several different types of analysis took place. The three interoperable file formats were analyzed and compared. The CAD software's import/export capabilities were analyzed and compared. The data analysis was based on preservation of information. Preservation of information meaning when file type A is converted to file type B, does file type B contain the same information file type A has. If the two files are not the same then file type B will be analyzed to determine what information is missing.

The CAD models were converted into many different formats and imported into many of the CAD programs. Table 3.1 shows what each of the CAD programs could export and/or import related to other native CAD and interoperable file formats. The source CAD systems (Z) are listed on the top row. The target CAD programs (Y) and the interoperable file formats (Y) are listed in the first column on the left. In the table, E represents the ability to export and I represents the ability to import. For example, a program with E/I can both import and export the corresponding CAD file format where as a program with just E can only export the corresponding CAD file format.

Table 3.1 *Export/Import Capabilities of the Selected CAD Programs*

	Z				
Y	CA	NX	PE	AI	SW
CATIA V5	E/I	E/I	-	E/I	-
NX 7.5	-	E/I	-	I	I
Pro/E 5.0	-	I	E/I	I	I
Inventor 2012	-	-	I	E/I	I
SolidWorks 2010	-	I	I	I	E/I
JT	-	E/I	-	E/I	-
3D PDF	-	-	E		-
STEP	E/I	E/I	E/I	E/I	E/I

ITI's software CADIQ was used to analyze models after they were done with each translation. The models were loaded into CADIQ and compared with the benchmark model they originated from. The results from the testing were output by CADIQ in the form of a comma delimited text file. The comma delimited text file was then loaded into Microsoft Excel for analysis of the final results. CADIQ could not at the time of testing, read native Autodesk Inventor 2012 files. Because of this, Inventor was tested in CADIQ as a STEP file. This is a limitation to the research as stated before, since what happens during the translation process cannot be fully determined. Inventor could not be directly compared to other file formats, but some data was collected natively from the model like file size, centroid, area, and volume. All of the other data collected was based on CADIQ's testing of the STEP file created from the native Inventor benchmark model.

The 3D PDF file format at the time of testing could not be read natively by CADIQ. Because of this, CADIQ analyzed the STEP file that the PDF created when it was exported. Again, this is a limitation but it was tested anyway. A 3D PDF can be read and viewed in the free software Adobe Acrobat Reader. However, in order to create the 3D PDF file from all of the native file formats, Adobe Acrobat X was used. Once the files were converted to the 3D PDF format, they were converted into STEP by way of the Tetra 4D add-on. The Tetra 4D add-on provided the user with many tools, even allowing the user to modify a model and save the changes. However, the Tetra 4D add-on was not used for this purpose and was only used for the translation of a model from the 3D PDF file format to the STEP file format.

The results were compared to each other in various ways to help determine possible trends. If changes occurred in models between translation processes, then those changes were determined using percent change where applicable. Percent change was determined by the relative change between the original attribute of the model and the same attribute of the newly translated model. The mean absolute deviation was also calculated for changes in the models where it was applicable. The mean absolute deviation was determined to see how much variation existed in particular data sets. This helped determine how confident the tests could have been, repeated with the same results. Any trends found in the data were identified. The strengths of the trends and how they apply to the overall CAD process were discussed. A summary and conclusion ended the discussion of the results. Reflection on the positives of the research were discussed as well as the weaknesses. There will also be discussion about suggestions for future research in the CAD interoperability area.

3.3.1. Interoperable File Formats

The only non-native, interoperable, file formats used and tested were:

- STEP AP203 edition 2 (part of ISO 10303)
- JT 9.5:
  - Representation:
    - B-Rep.
    - XT B-Rep.
    - Facets
    - B-rep and Facets
  - File Structure:
    - Fully Shattered
    - Mimic
    - Monolithic
    - Per Part
- 3D PDF with PRC
  - B-rep

- B-rep & Tessellation

The JT formats tested included file structure to see if it has any effect on the results. The fully shattered file stored each of the product structure nodes in an individual file. The mimics file structure simply mimics the file structure of the original model file(s). Monolithic is a single JT file containing the assembly nodes and the parts. The per part file structure consists of all assembly nodes residing in a single JT file with each part of the assembly stored in their own JT file in a subdirectory with the same name as the assembly file.

The interoperable file formats were tested by exporting the native CAD model into an interoperable file format and then imported into all the CAD programs that were capable. The imported model was then compared to the original model for differences. Table 3.1 shows the import/export capabilities of the CAD programs that were used. Every CAD program that can export or import a file format was tested and compared. Some of the CAD systems were very limited in what they could import and export, therefore the amount of data they produced for a file format was limited or absent. The evaluation criteria for the interoperable file formats are listed in Section 3.3.3 below.

3.3.2. Benchmark CAD Model

Previous studies have not explained why a particular model was used or given any criteria the model had to meet in order to be used in the previous research. The BM will be exported from each of the CAD programs and imported into each of the CAD programs. For example, the CATIA BM was exported into a STEP file and then imported separately into Pro/E, Inventor, NX, SolidWorks, and from each of those systems back into CATIA. The CATIA BM was also exported as a STEP file and checked for conformity with the STEP definition by way of 3rd party translation.

Evaluation Criteria for creation of the BM:

- Complexity of individual parts
- Number of parts in assembly
- Colors

- PMI
    - GD&T (Geometric Dimensioning and Tolerancing)
    - Picture, polyline, or integrated
    - Special PMI characters, i.e. center line
- Various fonts
- Level of construction history detail
- Amount of metadata
- Textures
- Applied Materials
- Size of file

3.3.3. Evaluation Criteria

Evaluation criteria for the CAD programs and interoperable file formats:

- Import/export options available for the interoperable file formats in each CAD program.
- Gaps (structural error as defined in section 2.4):
    - Quantity
    - Maximum length
- High-Curvature Curves
    - Quantity
    - Maximum curvature (minimum radius of curvature) value
- Deviation of centroid
- Deviation of volume
- Deviation of area
- Preservation of constraints
- PMI
    - GD&T
    - Picture, polyline, or integrated
    - Special PMI characters, e.g. center line

    - Various fonts
- Preservation of material properties and graphics

The data collected was compared and contrasted with other similar data from other models. All of the file formats were looked at to evaluate if the translation process produces consistent errors.

3.3.4. Third Party Software

The third party software CADIQ was used to analyze and compare the three interoperable file formats and the native CAD file formats. CADIQ could read the native format of the CAD program allowing for no loss in any data for the analysis. Many other third party analysis programs use their own proprietary file format to analyze models. This means that the native file format must first be translated into the proprietary file format before it can be analyzed. This can lead to possible loss of data. Any translation process can lead to possible loss of data. CADIQ avoided this.

CADIQ could natively read all of the file formats being tested except for Autodesk Inventor 2012 and 3D PDF. These were limitations as previously mentioned in Section 1.6. However, they were tested using the STEP file format. This did not allow for accurate and precise measurements of the models. Through the analysis and results of all other data, the capabilities of Inventor and PDF were generalized.

The 3D PDFs were created using Adobe Acrobat X with the Tetra 4D add-on. This was used because only Pro/ENGINEER has the ability to export a model as a 3D PDF.

3.3.4.1 CADIQ Analysis

CADIQ can analyze many different aspects of a model and collect many different types of data from the model. However, because of the scope of the research and the time that was available to collect, analyze, and organize the results, not all of the data CADIQ can collect was analyzed and organized.

Gaps in this research were determined by CADIQ's results of both edge gaps and edge face gaps. Edge gaps are defined by CADIQ as the distance between endpoints of edges connected at a vertex. Edge face gaps are defined by CADIQ as the distance between an edge and its underlying face. The number of gaps and the maximum value for each model was determined. CADIQ was also used to determine high-curvature curves. High-curvature curves are defined by CADIQ as the curve radius of curvature (CADIQ, 2011).

> The radius of curvature is measured at the midpoint of each segment and at each interior segment boundary. If the curve only has one segment, the radius of curvature is measured at three evenly spaced, interior parameters. The radius of curvature is not measured at the ends of the curve to avoid numerical instability problems. (CADIQ, 2011, p. 140)

CADIQ calculates the percent change in the centroid from model to model. However, CADIQ's centroid deviation results were not used in this research because CADIQ could not analyze the centroid deviation for all of the file formats used in this research. Therefore, the centroid deviation was found by determining the absolute percent difference between the centroids, the models from CADIQ results and those found natively for a CAD file format.

Due to the issue of numerical instability, all centroid calculations were used with results that had no more than a two times difference in magnitude. Numerical instability was due to large difference in magnitude and floating point calculations. A significant portion of the centroid results were numerically stable without omitting any data points. Any data points that resulted in zero after truncation were not used in calculating the deviation of the centroid from model to model. The effect omitting certain data points had on the confidence interval was minimal. For example, the sample set with the most numerical instability had an absolute average change of 1E+11%. After omitting the numerically unstable data points, the absolute average change was 30%. For the same sample set the resulting change in the confidence interval was from 5.27 to 5.56.

CADIQ used precise analysis for all of the CAD program criteria, but it only had approximate analysis for some of the mass properties of STEP. CADIQ only used approximate analysis to determine the volume and centroid of the STEP models. All of the mass property calculations for the JT file format are precise.

3.4. Process of Selecting Experts and Survey Outline

The benchmark model was used for analysis of the CAD programs and the third party software. However, not all of this determined if the benchmark model meets all of the criteria, a model should have to be considered for possible use in other testing. The benchmark model was validated by using experts in CAD translation and CAD modeling. The survey attempted to determine how appropriate the benchmark model was for the testing in this study and if it could be used in testing in industry. Expertise was determined by the knowledge attained over time by spending years working in a single domain, a person who has a degree(s) and a certificate(s) based on their years of work in that specific domain, and a person who is recognized by their peers as an expert.

Based on the previously mentioned description of an expert, the experts for this experiment were chosen based on the following criteria:

- Education
- Experience/Time
- Certifications
- Belonging to expert consortiums or societies
- Published work
- Availability
- Wiliness to participate
- Timely response

The survey consisted of one set of questions emailed to possible experts. The possible experts to be emailed were gathered from a list of professional contacts from various industries. They were emailed with an introductory page explaining the nature of the research and how the survey pertains to it. They were given the choice of participating and clicking on the provided link to be taken to the survey site. They then read a consent narrative and were asked if they would like to participate. Following the consent form they filled out the survey and submitted it electronically. Approximately one week after receiving the first email the participants were sent another email reminding them about the survey if they have not answered it already. The two emails and the survey can be found in Appendix D.

The survey consisted of 46 questions that attempted to determine if the benchmark model used in the research was adequate for the testing compared to models used in various industries. The survey also attempted to determine where the benchmark model could be improved upon and if the participants thought a benchmark model could be used for testing in industries.

The survey consisted of 46 questions and was estimated to take between 25 and 30 minutes. The survey was a mix of both quantitative and qualitative questions attempting to answer:

- Any complex functions that are missing that should be included?
- Appropriate number of parts in the assembly?
- Appropriate GD&T?
- Overall opinion of how they feel about the model related to use for testing in industry?
- Is there anything to add or leave out of the model?

The survey sample size was to be at least 15 participants who meet the previously stated criteria for an expert. The minimum sample size was to be 15 participants. The primary factors in determining a minimum sample size of 15 was the quantitative and qualitative nature of the questions, the goal of the research, and the specific type of participant required. Other factors were also taken into account for the sample size, the length of the survey, and the timeframe the survey could have been available (Borg & Gall, 1979; Lindolf, 1995; Marshall, 1996).

3.5. Possible Bias

The framework of this study is to reduce bias as much as possible with current technologies. Some of the results, which will be explicitly identified, should be generalizable to other software programs and interoperable file formats. However, the results presented are used with solid models made in a specific order and with specific techniques. Each CAD package is different and therefore handles standard modeling techniques differently. This needs to be taken into account when analyzing the results. These results also in no way determine how the software used or the interoperable file formats will handle surface or wireframe models or modeling techniques.

3.6. Chapter Summary

This chapter presented the framework of the research for the thesis. The models on which all the research is based were defined. The software being used and any possible bias were discussed. The framework for the data analysis was explained.

CHAPTER 4 PRESENTATION OF DATA

4.1. Introduction

As described in previous chapters, the purpose of this study is to determine how STEP AP203, JT, 3D PDF, and constraint-based native CAD file formats' capabilities compare to each other with regards to preservation of information. A benchmark model, CAD programs, third party software, and a survey are used to create the test models and analyze them.

The results will use abbreviations representing the translation path of the model and the subsequent file format of the model. The nomenclature used is for the presentation of the results in a concise manner. Refer to section 1.9 in Chapter 1 for a complete explanation of the nomenclature used.

This chapter presents the data from the creation and analysis of the CAD models, as well as the results of the survey given to industry professionals. The chapter begins with the data from the industry models and the data gathered from the making of the models in each CAD system. Then, the data gathered from CADIQ is presented with descriptions of the data. The survey data is presented last. An in-depth analysis and summation of the data will be discussed in Chapter 5.

4.2. Industry Model Data and Resulting Benchmark Model

There are five CAD systems used for testing, however, only four industry models were obtained for analysis. An industry model was obtained for all of the CAD systems except for NX 7.5. The four industry models were analyzed to determine various attributes and the results can be seen in the following table, Table 4.1.

Table 4.1 *Industry Model and Resulting Benchmark Model Specifications*

	CA	AI	NX	PE	SW	Average	BM
Total File Size (MB)	11.1	3.97	N/A	4.91	45.1	16.3	Varying
# of Sub-Assemblies	2	2	N/A	3	2	2.3	1.0
# of Parts	37	48	N/A	31	119	58.8	33.0
# of Unique Parts	37	16	N/A	18	30	25.3	29.0
# of Standard Parts (Part Library)	0	6	N/A	9	23	9.5	8.0
# of Unique Std. Parts	0	2	N/A	4	4	2.5	4.0
# of Applied Materials (graphic)	20	15	N/A	14	10	14.8	4.0
# of Applied Material properties	2	2	N/A	0	1	1.3	4.0
Detailed Feature Tree	Yes	Yes	N/A	Yes	No	75%	Yes
GD&T	Yes	No	N/A	Yes	No	50%	Yes
> Picture	-	-	-	-	-	-	-
> Polyline	-	-	-	-	-	-	-
> Integrated	Yes	-	-	Yes	-	100%	Yes

In the far right column of Table 4.1 the specifications of the resulting Benchmark Model (BM) are given. The resulting BM is based on the Industry Models (IM) and that this study is to determine the capabilities not including capacity. The BM has a varying file size because it was created in five different CAD systems. The detailed feature tree in Table 4.1 represents that the model had features on the tree that are renamed specifically for that particular model. By renaming the features in the tree, any person can better understand the model. This is also useful when translating a model if the translation keeps the feature or uses the names to describe a feature.

The benchmark model was created in all five CAD programs and a visualization of the benchmark model can be seen in *Figure 4.1* and *Figure 4.2* below.

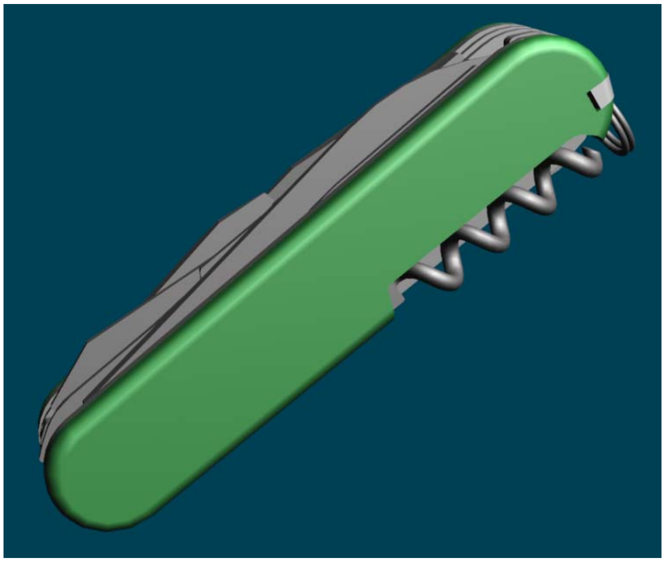

Figure 4.1 Closed view of the benchmark model

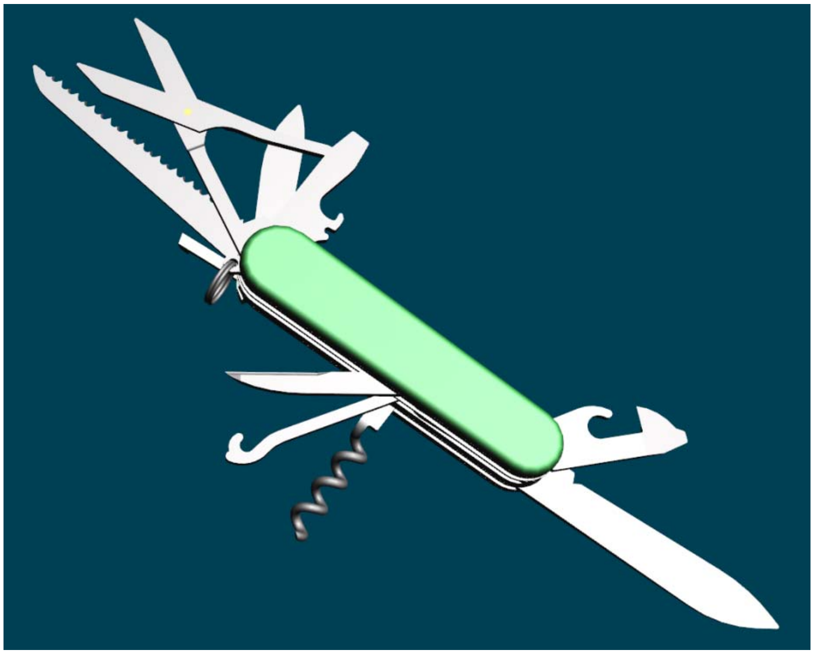

Figure 4.2 Open view of the benchmark model

Table 4.2 *List of Parts in the Benchmark Model and their Count*

Knife Assembly	Count:
Big Knife	1
Bottle Opener	1
Bottom Cover	1
Corkscrew	1
Flat Head	1
Hook	1
ISO M1.6x16	2
ISO M2x16	2
ISO Nut M1.6	2
ISO Nut M2	2
Key Ring	1
Little Knife	1
Pick	1
Saw	1
Scissor Assembly:	-
Scissor A	1
Scissor B	1
Scissor Screw	1
Separation Plate A	1
Separation Plate B	1
Separation Plate C	1
Separation Plate D	1
Separation Plate E	1
Separation Plate F	1
Support AB	1
Support BC	1
Support CD	1
Support DE	1
Toothpick	1
Top Cover	1
Total:	33

The benchmark model was based off of similar looking utility knives and has a one to one scale with various similar looking utilities knives. Various features were used to create the benchmark model not clearly visible from the figures above:

- Various off-set planes
- Complex feature patterns
- Countersunk holes (feature based)
- Complex fillets
- Mirrored geometry
- Splines
- Different custom colors associated with each material

A list of the unique parts created and how many times they were used can be found in Table 4.2 above.

Product manufacturing information (PMI) was embedded in the BM in each of the CAD programs. PMI including geometric dimensioning and tolerancing, special characters (e.g. center line), and various fonts. All of the CAD programs did not have the same fonts or special characters available. An example of some of the PMI can be seen in *Figure 4.3* and *Figure 4.4* below.

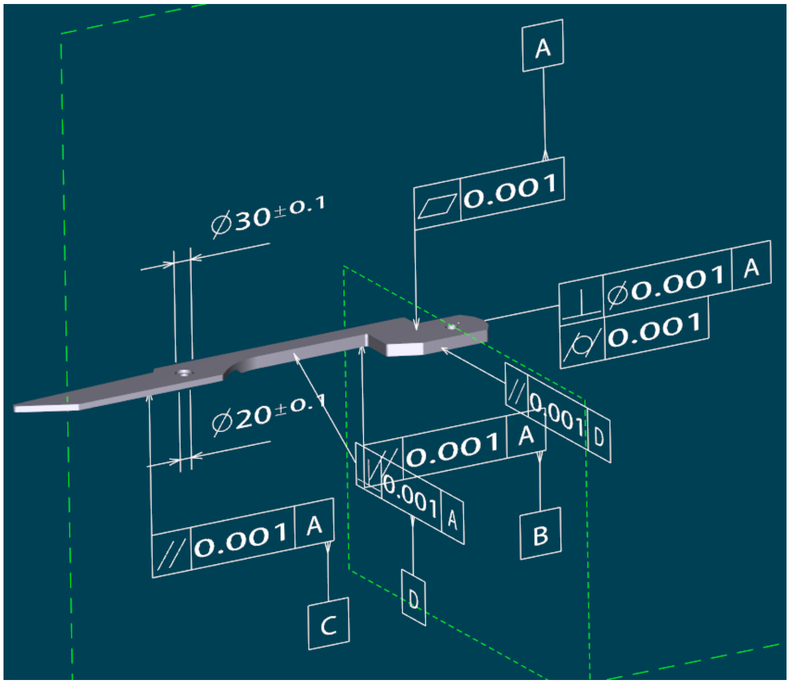

Figure 4.3 Example one of PMI used

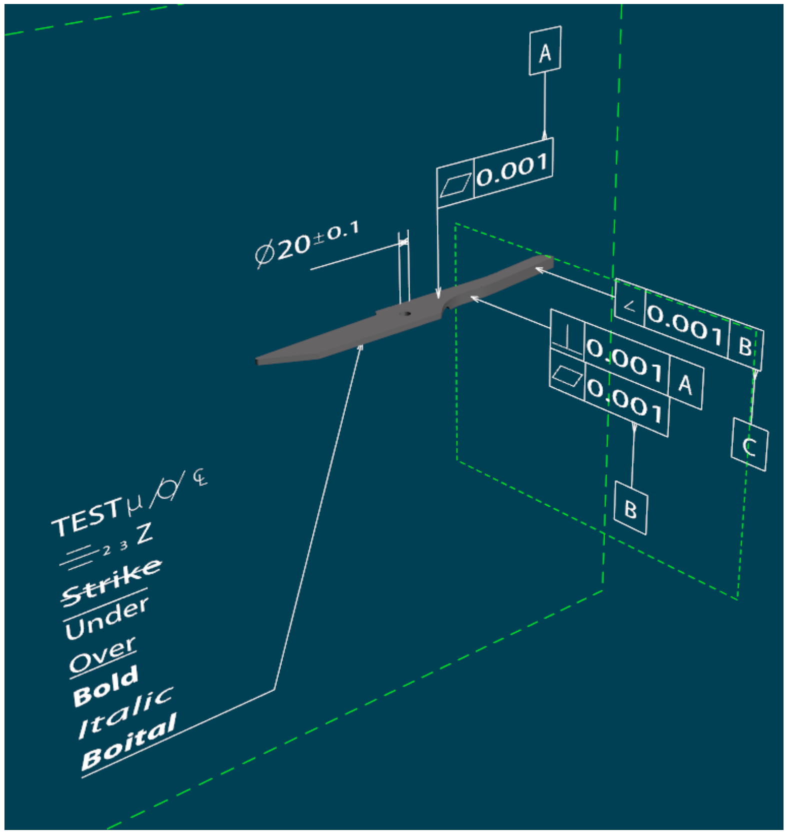

Figure 4.4 Example two of PMI used

4.3. <u>Import/Export Capabilities of the Five CAD Programs</u>

The five CAD programs chosen for the study have varying abilities to import and export specific file formats. Table 4.2 shows what each of the CAD programs can export and/or import related to other native CAD and interoperable file formats. The source CAD systems are listed on the top of each column and the target CAD systems are listed in the first column on the left.

Table 4.3 *Export/Import Capabilities of the Selected CAD Programs*

		Z				
		CA	NX	PE	AI	SW
Y	CATIA V5	E/I	E/I	-	E/I	-
Y	NX 7.5	-	E/I	-	I	I
Y	Pro/E 5.0	-	I	E/I	I	I
Y	Inventor 2012	-	-	I	E/I	I
Y	SolidWorks 2010	-	I	I	I	E/I
	JT	-	E/I	-	E/I	-
	3D PDF	-	-	E		-
	STEP	E/I	E/I	E/I	E/I	E/I

CATIA and NX are the only CAD programs of the five to offer non-standard options when importing and exporting the STEP file format. CATIA and NX have the capability of exporting models as a single file or the more standard option of having a STEP file for every model file. CATIA also has the option of importing STEP files using continuity optimization of curves and surfaces. Available are three options, no optimization, automatic optimization, and advanced optimization. These options were tested and determined to have no more than a 0.0003 percent difference, if any, between them for any of the criteria analyzed.

4.4. File Size, Area, & Volume Translation Results

In this section, the model file sizes, area, and volume will be presented broken into exported and imported results. CADIQ, the software used to analyze the file formats, cannot read the 3D PDF file format or the Autodesk Inventor native file format, therefore these files will be translated to STEP and then analyzed in CADIQ. Because Autodesk Inventor cannot be natively analyzed by CADIQ, native area and volume were determined using Inventor. Curve and gap analysis was not done on native AI models because only the CADIQ software can test for curves and gaps. The results are presented with the average absolute change and the mean absolute deviation (m.a.d.).

The following results in this section are the file sizes of the end file format compared to the native benchmark it came from. The file size is compared to the original benchmark and is given as a percentage of the original size. The standard deviation is also given for the file size percentage of the original.

4.4.1. CAD Results

Table 4.4 *CAD Export, Percent of Original Benchmark Model File Size*

		STEP	JT	3D PDF
CATIA V5	%	59.71%	n/a	-
	m.a.d.	23.90%	n/a	-
Inventor	%	75.92%	64.18%	-
	m.a.d.	7.01%	25.74%	-
NX 7.5	%	76.21%	74.83%	-
	m.a.d.	3.40%	14.92%	-
Pro/E	%	79.64%	n/a	7.97%
	m.a.d.	5.07%	n/a	22.62%
SolidWorks	%	47.00%	n/a	-
	m.a.d.	15.21%	n/a	-

The results in Table 4.4, above, were found using the file size of the original native CAD BM and the resultant exported STEP file.

Table 4.5 *CAD Export, Absolute Change in Area*

		STEP	JT	3D PDF
CATIA V5	%	5.30%	-	-
	m.a.d.	9.72%	-	-
Inventor	%	10.52%	8.99%	-
	m.a.d.	19.25%	17.32%	-
NX 7.5	%	14.68%	12.60%	-
	m.a.d.	28.85%	23.46%	-
Pro/E	%	0.07%	-	n/a
	m.a.d.	0.09%	-	n/a
SolidWorks	%	2.87%	-	-
	m.a.d.	5.48%	-	-

Table 4.6 *CAD Export, Absolute Change in Volume*

		STEP	JT	3D PDF
CATIA V5	%	5.76%	-	-
	m.a.d.	10.27%	-	-
Inventor	%	13.22%	7.16%	-
	m.a.d.	24.36%	13.32%	-
NX 7.5	%	0.0004%	12.56%	-
	m.a.d.	0.0006%	24.24%	-
Pro/E	%	0.19%	-	n/a
	m.a.d.	0.25%	-	n/a
SolidWorks	%	4.16%	-	-
	m.a.d.	7.98%	-	-

The results in Table 4.5 and Table 4.6, above, are the average absolute change. The results were found using the original native CAD benchmark model and their respective exported STEP file.

Table 4.7 *Overall CAD Export Absolute Changes*

		STEP	JT	3D PDF
File Size	%	67.71%	69.93%	7.97%
	m.a.d.	17.51%	19.97%	22.62%
Area	%	6.97%	11.13%	-
	m.a.d.	13.26%	21.01%	-
Volume	%	3.88%	9.34%	-
	m.a.d.	7.17%	17.64%	-

The results in Table 4.7, above, are the combined results for all CAD program exports.

Table 4.8 *CAD Import, Absolute Change in Area*

		STEP	JT	3D PDF
CATIA V5	%	4.98%	n/a	-
	m.a.d.	9.54%	n/a	-
Inventor	%	4.49%	2.18%	-
	m.a.d.	8.66%	4.03%	-
NX 7.5	%	6.53%	0.01%	-
	m.a.d.	12.74%	0.02%	-
Pro/E	%	2.44%	n/a	-
	m.a.d.	4.60%	n/a	-
SolidWorks	%	0.07%	n/a	-
	m.a.d.	0.09%	n/a	-

Table 4.9 *CAD Import, Absolute Change in Volume*

		STEP	JT	3D PDF
CATIA V5	%	4.61%	n/a	-
	m.a.d.	8.68%	n/a	-
Inventor	%	4.49%	1.42%	-
	m.a.d.	8.35%	2.24%	-
NX 7.5	%	2.36%	0.00%	-
	m.a.d.	4.24%	0.00%	-
Pro/E	%	2.10%	n/a	-
	m.a.d.	3.73%	n/a	-
SolidWorks	%	0.18%	n/a	-
	m.a.d.	0.24%	n/a	-

Table 4.10 *Overall CAD Import Absolute Changes*

		STEP	JT	3D PDF
File Size	%	-	-	-
	m.a.d.	-	-	-
Area	%	4.56%	0.54%	-
	m.a.d.	8.76%	1.02%	-
Volume	%	3.89%	0.65%	-
	m.a.d.	7.28%	1.11%	-

4.4.2. 3D PDF Results

Since CADIQ cannot read native 3D PDF, the files were exported to STEP from PDF and then analyzed. The results in Table 4.20, below, were found using the exported STEP models from PDF compared to the original native CAD models they were translated from. The results in Table 4.11, below, were found using the original native CAD models and the resultant native PDF models from all of the translations.

Table 4.11 *Overall PDF (analyzed as STEP files) Absolute Changes*

	File Size	Area	Volume
Average	72.42%	1.87%	2.09%
Mean Abs. Dev.	18.47%	3.51%	3.71%

Table 4.12 *Overall Native PDF from CAD Absolute Changes*

	File Size	Area	Volume
Average	70.27%	n/a	n/a
Mean Abs. Dev.	19.13%	n/a	n/a

4.4.3. Native CAD File Format Results

This section presents the results for CAD programs importing and exporting other native CAD file formats. The specific translation paths can be found by referencing Table 4.4. CATIA V5 is not included in the following results because it cannot import or export any of the other four's native file formats.

Table 4.13 *CAD Import, Absolute Changes*

		Volume	Area
AI import CA	avg.	12.75%	0.004%
	m.a.d.	22.67%	0.007%
AI import NX	avg.	41.71%	42.39%
	m.a.d.	62.56%	63.59%
AI import PE	avg.	0.23%	0.001%
	m.a.d.	0.31%	0.002%
AI import SW	avg.	0.10%	0.02%
	m.a.d.	0.14%	0.03%
NX import SW	avg.	0.0001%	0.0001%
	m.a.d.	0.0001%	0.0003%
NX import CA	avg.	0.002%	0.001%
	m.a.d.	0.003%	0.001%
PE import AI	avg.	1.17%	6.44%
	m.a.d.	1.81%	11.18%
SW import AI	avg.	12.80%	9.28%
	m.a.d.	24.71%	17.90%
SW import NX	avg.	3.57%	3.69%
	m.a.d.	6.89%	7.11%

Table 4.14 *Overall CAD Import Absolute Changes*

	File Size	Area	Volume
Average	74%	5%	5%
Mean Abs. Dev.	19%	10%	9%

Table 4.15 *CAD Export, Absolute Changes*

		Volume	Area
AI to CA	avg.	12.81%	9.28%
	m.a.d.	24.70%	17.90%
NX to CA	avg.	0.14%	0.14%
	m.a.d.	0.22%	0.23%
SW to PE	avg.	0.001%	0.001%
	m.a.d.	0.001%	0.002%

Table 4.16 *Overall CAD Export Absolute Changes*

	File Size	Area	Volume
Average	46%	3%	4%
Mean Abs. Dev.	24%	6%	8%

4.5. Centroid Translation Results

The following section presents the absolute change in the centroid for the model translations. How the absolute change in the centroid was determined can be found in Section 3.3.4.1.

4.5.1. CAD Results

Table 4.17 *CAD Export, Absolute Change in Centroid*

		STEP	JT	3D PDF
CATIA V5	%	21.05%	-	-
	m.a.d.	9.56%	-	-
Inventor	%	15.71%	6.72%	-
	m.a.d.	10.71%	0.03%	-
NX 7.5	%	9.11%	7.21%	-
	m.a.d.	0.0001%	0.001%	-
Pro/E	%	13.29%	-	n/a
	m.a.d.	7.51%	-	n/a
SolidWorks	%	16.11%	-	-
	m.a.d.	7.68%	-	-

Table 4.18 *Overall CAD Export, Absolute Change in Centroid*

		STEP	JT	3D PDF
Centroid	%	24.58%	7.02%	-
	m.a.d.	7.99%	0.002%	-

Table 4.19 *CAD Import, Absolute Change in Centroid*

		STEP	JT	3D PDF
CATIA V5	%	23.84%	n/a	-
	m.a.d.	7.51%	n/a	-
Inventor	%	12.06%	13.26%	-
	m.a.d.	1.16%	7.15%	-
NX 7.5	%	27.27%	9.29%	-
	m.a.d.	14.14%	0.00%	-
Pro/E	%	28.78%	n/a	-
	m.a.d.	18.19%	n/a	-
SolidWorks	%	25.10%	n/a	-
	m.a.d.	6.49%	n/a	-

Table 4.20 *Overall CAD Import, Absolute Change in Centroid*

		STEP	JT	3D PDF
Centroid	%	17.32%	10.93%	-
	m.a.d.	8.24%	0.001%	-

4.5.2. 3D PDF Results

The results in Table 4.21 were found using the STEP file format, which was exported natively from the PDF file format. The results to Table 4.22 were not available because CADIQ cannot analyze native PDF files.

Table 4.21 *Overall PDF, Absolute Change in Centroid*

	PDF
Average	19%
Mean Abs. Dev.	8%

Table 4.22 *Overall PDF from CAD, Absolute Change in Centroid*

	PDF
Average	n/a
Mean Abs. Dev.	n/a

4.5.3. Native CAD File Format Results

Table 4.23 *CAD Import, Absolute Change in Centroid*

		Centroid
AI import CA	avg.	29.76%
	m.a.d.	32.91%
AI import NX	avg.	14.27%
	m.a.d.	13.63%
AI import PE	avg.	13.30%
	m.a.d.	12.70%
AI import SW	avg.	13.24%
	m.a.d.	12.65%
NX import SW	avg.	0.32%
	m.a.d.	0.63%
NX import CA	avg.	2.53%
	m.a.d.	0.0004%
PE import AI	avg.	4.70%
	m.a.d.	0.00%
SW import AI	avg.	17.58%
	m.a.d.	33.24%
SW import NX	avg.	5.87%
	m.a.d.	11.44%

The result for the mean absolute deviation in Table 4.23 above is not actually zero but 1.15E-05 percent for PE.

Table 4.24 *Overall CAD Import, Absolute Change in Centroid*

	Centroid
Average	13%
Mean Abs. Dev.	0%

The result for the mean absolute deviation in Table 4.24 above is not actually zero but 2.07E-04 for all of the translation paths in CAD imports.

Table 4.25 *CAD Export, Absolute Change in Centroid*

		Centroid
AI to CA	avg.	2.40%
	m.a.d.	0.002%
NX to CA	avg.	20.64%
	m.a.d.	36.35%
SW to PE	avg.	13.07%
	m.a.d.	0%

Table 4.26 *Overall CAD Export, Absolute Change in Centroid*

	Centroid
Average	6%
Mean Abs. Dev.	0%

The result for the mean absolute deviation in Table 4.26 above is not actually zero but 4.04E-04 for all of the translation paths in CAD exports.

4.6. Gap & Curve Translation Results

The following section presents the results from the research regarding gap and curve analysis. The results are the average change in the amount of gaps and curve, as well as the maximum gap values and maximum curvature (minimum radius of curvature) value.

4.6.1. Interoperable File Format Results

Table 4.27 *CAD Export, Absolute Average Change in Number of High-Curvature Curves*

		STEP	JT	3D PDF
CATIA V5	%	3.99%	-	-
	m.a.d.	4.87%	-	-
Inventor	%	n/a	12.99%	-
	m.a.d.	n/a	16.95%	-
NX 7.5	%	n/a	42.51%	-
	m.a.d.	n/a	51.73%	-
Pro/E	%	19.13%	-	n/a
	m.a.d.	5.17%	-	n/a
SolidWorks	%	40.63%	-	-
	m.a.d.	32.27%	-	-

Table 4.28 *CAD Export, Absolute Average Change in Number of Gaps*

		STEP	JT	3D PDF
CATIA V5	%	0.00%	-	-
	m.a.d.	0.00%	-	-
Inventor	%	n/a	16.38%	-
	m.a.d.	n/a	22.28%	-
NX 7.5	%	n/a	48.26%	-
	m.a.d.	n/a	62.01%	-
Pro/E	%	0.00%	-	n/a
	m.a.d.	0.00%	-	n/a
SolidWorks	%	34.54%	-	-
	m.a.d.	24.59%	-	-

Table 4.29 *CAD Export, Minimum Radius of Curvature (mm)*

		STEP	JT	3D PDF
CATIA V5	avg.	0.57	-	-
	m.a.d.	0.28	-	-
Inventor	avg.	n/a	0.65	-
	m.a.d.	n/a	0.29	-
NX 7.5	avg.	n/a	0.61	-
	m.a.d.	n/a	0.29	-
Pro/E	avg.	0.55	-	n/a
	m.a.d.	0.28	-	n/a
SolidWorks	avg.	0.57	-	-
	m.a.d.	0.28	-	-

Table 4.30 *CAD Export, Maximum Gap Value (mm)*

		STEP	JT	3D PDF
CATIA V5	%	8.00E-05	-	-
	m.a.d.	1.20E-04	-	-
Inventor	%	n/a	2.38E-03	-
	m.a.d.	n/a	3.30E-03	-
NX 7.5	%	n/a	5.80E-04	-
	m.a.d.	n/a	7.90E-04	-
Pro/E	%	3.20E-04	-	n/a
	m.a.d.	5.40E-04	-	n/a
SolidWorks	%	1.70E-04	-	-
	m.a.d.	2.80E-04	-	-

Table 4.31 *Overall CAD Export, Absolute Changes*

		STEP	JT	3D PDF
H.C. Curves	%	14.35%	30.19%	-
	m.a.d.	14.11%	38.10%	-
HCC Values (mm)	avg.	0.56	0.63	-
	m.a.d.	0.28	0.29	-
Gaps	%	6.91%	35.15%	-
	m.a.d.	11.22%	46.33%	-
Gap Values (mm)	avg.	0.0001	0.001	-
	m.a.d.	0.0002	0.002	-

The following results are for the CAD program's native import of the STEP file format.

Table 4.32 *CAD Import, Absolute Average Change in Number of High-Curvature Curves*

		STEP	JT	3D PDF
CATIA V5	%	17.86%	n/a	-
	m.a.d.	22.72%	n/a	-
Inventor	%	17.04%	8.49%	-
	m.a.d.	12.21%	10.15%	-
NX 7.5	%	n/a	153.0%	-
	m.a.d.	n/a	202.6%	-
Pro/E	%	15.32%	n/a	-
	m.a.d.	16.58%	n/a	-
SolidWorks	%	127.76%	n/a	-
	m.a.d.	240.45%	n/a	-

Table 4.33 *CAD Import, Absolute Average Change in Number of Gaps*

		STEP	JT	3D PDF
CATIA V5	%	18.75%	n/a	-
	m.a.d.	24.23%	n/a	-
Inventor	%	19.40%	9.47%	-
	m.a.d.	14.21%	11.59%	-
NX 7.5	%	n/a	59.51%	-
	m.a.d.	n/a	114.07%	-
Pro/E	%	16.53%	n/a	-
	m.a.d.	20.06%	n/a	-
SolidWorks	%	0.07%	n/a	-
	m.a.d.	0.13%	n/a	-

Table 4.34 *CAD Import, Minimum Radius of Curvature (mm)*

		STEP	JT	3D PDF
CATIA V5	%	0.58	n/a	-
	m.a.d.	0.28	n/a	-
Inventor	%	0.61742	0.63	-
	m.a.d.	0.27	0.27	-
NX 7.5	%	n/a	0.59	-
	m.a.d.	n/a	0.27	-
Pro/E	%	0.55	n/a	-
	m.a.d.	0.28	n/a	-
SolidWorks	%	0.58	n/a	-
	m.a.d.	0.28	n/a	-

Table 4.35 *CAD Import, Maximum Gap Value (mm)*

		STEP	JT	3D PDF
CATIA V5	%	4.80E-04	n/a	-
	m.a.d.	8.30E-04	n/a	-
Inventor	%	1.70E-04	0.0002	-
	m.a.d.	3.00E-04	0.0004	-
NX 7.5	%	n/a	9.98	-
	m.a.d.	n/a	15.76	-
Pro/E	%	5.40E-04	n/a	-
	m.a.d.	5.70E-04	n/a	-
SolidWorks	%	2.30E-04	n/a	-
	m.a.d.	3.90E-04	n/a	-

Table 4.36 *Overall CAD Import, Absolute Changes*

		STEP	JT	3D PDF
H.C. Curves	%	32.68%	112.00%	-
	m.a.d.	45.61%	146.31%	-
HCC Values (mm)	avg.	0.58	0.60	-
	m.a.d.	0.27	0.27	-
Gaps	%	15.50%	45.32%	-
	m.a.d.	18.64%	82.44%	-
Gap Values (mm)	avg.	0.0004	7.148	-
	m.a.d.	0.0006	12.079	-

4.6.2. 3D PDF Results

Since CADIQ cannot read native 3D PDF the files were exported to STEP from PDF and then analyzed.

Table 4.37 *Overall PDF Export to STEP Absolute Changes*

	Curves	Min Curve Values	Gaps	Max Gap Values
Average	18%	0.55726	13%	0.00295
Mean Abs. Dev.	15%	0.27371	19%	0.00532

Table 4.38 *Overall PDF from CAD Absolute Changes*

	Curves	Min Curve Values	Gaps	Max Gap Values
Average	n/a	n/a	n/a	n/a
Mean Abs. Dev.	n/a	n/a	n/a	n/a

4.6.3. Native CAD File Format Results

The following results in this section are data for gaps and curves from model CAD programs imported and exported directly to or from other CAD program’s native file format.

Table 4.39 *CAD Import, Absolute Changes*

		H.C. Curves	HCC Values (mm)	Gaps	Gap Values (mm)
AI import CA	avg.	14.07%	0.61684	18.56%	0.0004
	m.a.d.	9.83%	0.26943	14.18%	0.0007
AI import NX	avg.	0.70%	0.61503	1.05%	0.0338
	m.a.d.	1.29%	0.27031	1.95%	0.0661
AI import PE	avg.	32.01%	0.61328	18.70%	0.0001
	m.a.d.	11.01%	0.27115	14.69%	0.0002
AI import SW	avg.	9.91%	0.63386	0.43%	0.0338
	m.a.d.	14.04%	0.27202	0.80%	0.0661
NX import SW	avg.	9.29%	0.64212	0.00%	0.0001
	m.a.d.	13.43%	0.26746	0.00%	0.0002
NX import CA	avg.	30.02%	0.56871	35.75%	0.0005
	m.a.d.	27.88%	0.27629	34.10%	0.0005
PE import AI	avg.	43.02%	0.58955	47.17%	0.0005
	m.a.d.	19.31%	0.26738	30.17%	0.0005
SW import AI	avg.	3.44%	0.64389	1.44%	0.0006
	m.a.d.	5.70%	0.26211	2.57%	0.0011
SW import NX	avg.	7.40%	0.64153	4.80%	0.0000
	m.a.d.	11.82%	0.26475	9.22%	0.0000

The following results in Table 4.40, is the overall from all of the CAD programs directly importing and exporting other CAD program's native file format.

Table 4.40 *CAD Export, Absolute Changes*

		H.C. Curves	HCC Values (mm)	Gaps	Gap Values (mm)
AI to CA	avg.	25.91%	0.62346	33.33%	0.0004
	m.a.d.	22.59%	0.26124	30.73%	0.0007
NX to CA	avg.	15.91%	0.60512	20.16%	0.0001
	m.a.d.	12.30%	0.27546	15.94%	0.0001
SW to PE	avg.	40.63%	0.38226	34.54%	0.0001
	m.a.d.	32.27%	0.29763	24.59%	0.0002

Table 4.41 *Overall CAD Export Absolute Changes*

	Curves	Min Curve Values	Gaps	Max Gap Values
Average	32%	0.5188	35%	0.0003
Mean Abs. Dev.	28%	0.2715	30%	0.0005

4.7. Material Property Translation Results

The tables below show what material properties transferred. Other Properties include Young's modulus and other material properties. The translation results for PEPDF2ST are the Pro/ENGINEER native file export to PDF.

Table 4.42 *Translation Path Material Property Preservation, part 1*

	Color	Material Name	Density	Other Prop.
CA to ST	Y	N	N	N
ST to CA	Y	N	N	N
CA to PDF	Y	N	N	N
CA to PDF to ST	N	N	N	N
PE to ST	Y	N	Y	N
ST to PE	N	N	N	N
PE import AI	Y	N	N	N
PEPDF	Y	N	N	N
PEPDF2ST	n/a	n/a	n/a	n/a
PE PDF	Y	Y	Y	Y
PE to PDF to ST	Y	N	N	N
SW to ST	N	N	N	N
ST to SW	Y	N	N	N
SW import AI	Y	N	Y	N
SW import NX	N	N	N	N
SW to PE	Y	N	Y	N
SW to PDF	Y	N	Y	N
SW to PDF to ST	N	N	N	N

Table 4.43 *Translation Path Material Property Preservation, part 2*

	Color	Material Name	Density	Other Prop.
NX to ST	N	N	N	N
ST to NX	N	N	N	N
NX to JT	Y	N	Y	Y
JT to NX	Y	N	Y	Y
NX to PDF	Y	N	Y	N
NX to PDF to ST	N	N	N	N
NX import SW	N	N	N	N
NX import CA	N	N	N	N
NX to CA	N	N	N	N
AI to ST	Y	N	N	N
ST to AI	Y	N	N	N
AI to JT	N	N	N	N
JT to AI	Y	N	N	N
AI to PDF	Y	N	Y	N
AI to PDF to ST	N	N	N	N
AI import CA	Y	N	N	N
AI import NX	N	N	N	N
AI import PE	Y	N	N	N
AI import SW	Y	N	N	N
AI to CA	Y	N	N	N

4.8. PMI Translation Results

Tables 4.44, 4.45, and 4.46 show the PMI results from the research. The results below are representative for each of the file options possible along that specific path. It should be noted that the file translation path of CA to ST to AI did not have the same results as the other CA to ST to CAD paths.

Table 4.44 *Notable PMI Translation Text Related Results*

Model	Text Correct	Missing Special Ch.	Missing Normal Ch.	Integrated	Polyline	Picture	Adaptable
AI BM	X			X			
CA BM	X			X			X
CA to PDF		X			X		
CA to ST	X				X		
CA to ST to CA	X				X		
CA2ST2NX	X				X		
CA to ST to PE	X				X		
NX BM	X			X			
NX to JT	n/a	n/a	n/a	n/a	n/a	n/a	n/a
NX to PDF to ST		X	X		X		
PE BM	X			X			
PE to PDF		X	X		X		
PEPDF to ST	X				X		
SW BM	X			X			

Table 4.45 *Notable PMI Translation Datum Reference Related Results*

Model	Plane ID Correct	Plane ID Visible	Integrated	Polyline	Picture	Adaptable
AI BM	X		X			
CA BM	X	X	X			X
CA to PDF	X	X		X		
CA to ST	X	X		X		
CA to ST to CA	X	X		X		
CA to ST to NX	X	X		X		
CA to ST to PE	X	X		X		
NX BM	X	X	X			
NX to JT	n/a	n/a	n/a	n/a	n/a	n/a
NX to PDF to ST	X	X		X		
PE BM	X	X	X			
PE to PDF		X		X		
PEPDF to ST	X	X		X		
SW BM	X	X	X			

Table 4.46 *Notable PMI Translation Tolerancing Related Results*

Model	Tolerancing Visible	Tolerancing Correct	Integrated	Polyline	Picture	Adaptable
AI BM	X		X			
CA BM	X	X	X			X
CA to PDF				X		
CA to ST	X	X		X		
CA to ST to CA	X	X		X		
CA to ST to NX	X	X		X		
CA to ST to PE	X	X		X		
NX BM	X	X	X			
NX to JT	n/a	n/a	n/a	n/a	n/a	n/a
NX to PDF to ST	X	X		X		
PE BM	X	X	X			
PE to PDF				X		
PEPDF to ST				X		
SW BM	X	X	X			

Tables 4.44, 4.45, and 4.46 do not contain all of the PMI results, just the highlights. The rest of the translations did not have PMI available to modify or even view. The PMI results were obtained by visually checking every file containing PMI. The PMI was checked visually because this is how a user primarily interacts with PMI.

4.9. Survey Results

The survey was taken by 28 participants but only 17 finished. Some of the results are presented below. Answers to questions that allowed the participant to write freely will be shown. However, not all of the answers will be presented in this section, only a variety of the answers. The complete list of answers to the written response questions can be seen in Appendix C.

Two participants have six to ten years’ experience and one person has one to five years’ experience. Of the fourteen that answered ten plus years, twelve of them said that they would not consider themselves experts based on how they felt their peers viewed them. The two participants gave the reasons they felt their peers would not consider them experts to be:

- "Rather managing CAD than creating it"
- "the amount of expertise that I have acquired is limited to a small part of the CAD process."

The 14 participants that answered with ten plus years' experience, provided some of the answers to why they think their peers would view them as an expert are below. The answers below are those that did not give answers about time as an explanation:

- "Because of over 20 years of modeling and 40 + years in design…"
- "… have been certified in NX…"
- "… Used multiple CAD packages and training industry professionals…"
- "Math knowledge. Knowledge of NURBS algorithms."

When asked if the participants have any certifications related to CAD modeling five of them answered yes and four of them specified what certifications were in:

- "Siemen Cad Certification"
- "Autodesk Inventor AIC"
- "Autodesk Inventor Associate"
- "NX5 basics, from Siemens PLM"
- "Certifcates [sic] of completion from Unigraphics training classes in Design and Mfg"

The participants were asked if they belonged to any consortiums or societies and if they have published or given a professional presentation relating to CAD tools. Eleven participants said they belong to a consortium or society and thirteen said they have published an article or given a presentation.

Table 4.47 *Results to Survey Question Number 15*

What is your first impression of the model in terms of assembly complexity and number of parts? (Please mark all that apply and explain)

Answer	Response
Good assembly complexity	9
Good number of parts	9
Too simple assembly	6
Too few number of parts	4

The participants explained their answers to the question in Table 4.47 above, and a variety of the answers were:

- "… not complex enough for large industry such as auto or aerospace…"
- "This would be a good test for mid-range CAD systems, but not for high end systems"
- "The case would be considered simple in terms of number of parts, but reasonable example for comparison."
- "It looks like a reasonable number of parts for a benchmark."
- "The assembly is too simple. Typical customer assemblies are larget [sic] with more complex parts."

Question: What is your first impression of the model in terms of individual part complexity?

- "…The knife may not represent all the entity types you need for a benchmark… If a benchmark part is too big or complex, it becomes difficult to use."
- "The model was complex enough for the test."
- "Parts are simple. There aren't any complex surfaces."
- "Each part has the geometry that it should. No more, no less than necessary"

Question: What is your first impression of the model in terms of geometric dimensioning and tolerancing (GD&T)?

- “Pretty basic.”
- “They seem valid.”
- “First impression was what views were the GD&T created did not seem to be the appropriate view for the best viewing.”
- “The GD+T looks OK. However, there does not appear to be potential for weld information.”

Table 4.48 *Results to Survey Question Number19*

How does the model above in terms of number of parts relate to models you have interacted with in industry?

Answer	Response
High part count	0
Medium part count (about in the middle)	1
Low part count	7
I do not think the number of parts matters in having a benchmark model for testing	9

If the participants answered ‘I do not think the number of parts…’ to the question presented in Table 4.48 above, they were asked why and some of the answers were:

- “Once you get to 5 or 6 components – the rest is repeatitive [sic]. It is good to have an assembly of assemblies represented by the sissors [sic].”
- “Because each product is different thus different amounts of parts are required to describe it for manufacture.”
- “number of parts alone does not qualify for benchmark.”
- “A large number of parts to produce in each of the systems from the ground up will be time consuming. The more parts, the more difficult it will be to find where errors arise. Testing large models is a different set of issues, that it sounds like this is trying to compare.”
- “…It is more important that the range of modeling features be covered than there be a large number of parts.”

- "…Parts that have asthetic [sic] design requirements or deal with air of fluid flow of some kind are usually good candidates…"

Table 4.49 *Results to Survey Question Number 21*

When comparing this model to models you have interacted with in industry, this model should:

Answer	Response
have more sub-assemblies	4
stay with the one sub-assembly it has	7
have no sub-assemblies	0
the number of sub-assemblies does not matter	6

If the participants answered 'the number of sub-assemblies does not matter' to the question presented in Table 4.49 above, they were asked why and some of the answers were:

- "Again it's not quantity but complexity of the product…"
- "Assemblies are an outdated method of rating the complexity. Complexity is defined by count but also number of variants and variant restrictions…"
- "The number is less critical than ensuring all critical associations/relationships/conversions are properly addressed."

Table 4.50 *Results to Survey Question Number 23*

In your opinion, are the Corkscrew, Keyring, and Saw parts (shown above) geometrically complex?

Answer	Response
Yes	2
No	13
Too little information present.	2

If the participants answered 'too little information present' to the question presented in Table 4.50 above, they were asked why and some of the answers were:

- “All of the conponents [sic] seem to be fairly simple to generate and put together? But there may be hidden complesity [sic] that can't be determined viewing the result…”
- “I could not look into the PRC file to determine the complexity of the data…”

Thirteen participants answered yes, that the number of geometrically complex parts in an assembly matters. Some of their explanations are as follows:

- “No - but having different complexity represented in different parts of the assembly is desireable [sic] …”
- “Shows the flexibility [sic] and strength of the CAD Product.”
- “So that you can have a benchmark that other products can be matched up with that are similar in complexity and the number of parts.”
- “Because some users don´t believe in simple assemblies.”
- “production models are complex…”

Four participants answered no, that the number of geometrically complex parts in an assembly does not matter. Some of their explanations are as follows:

- “I think it can matter, but I think you have to work out the process and the results on the simpler set of cases first and then add other test cases as your process matures. Success or failure of exchange has lots of variables.”
- “As long as it is representative it should not matter.”

Table 4.51 *Results to Survey Question Number 25*

Does the number of geometrically complex parts in a potential benchmark assembly model matter?

Answer	Response
Yes	13
No	4

Table 4.52 *Results to Survey Question Number 28*

Does the potential benchmark assembly model above have a sufficient number of geometrically complex parts when comparing it to a model you might find in industry?

Answer	Response
Yes	5
No, should be more	8
No, should be less	0

Table 4.53 *Results to Survey Question Number 29*

Does the number of parts in a potential benchmark model matter?

Answer	Response
Yes	10
No	7

If the participants answered ‘Yes’ to the question presented in Table 4.53 above, they were asked why and some of the answers were:

- “If it is just entity accuracy accross [sic] CAD tools....it probably doesn't.”
- “How a CAD system utilizes Memory and Graphics is important once the users gets up to a larger assembly.”
- “It can, but again I think it is what you want ot [sic] test. If you want to test scalability then the number of parts matters…

If the participants answered ‘No’ to the question presented in Table 4.52 above, they were asked why and some of the answers were:

- “Because once you have 5 or 6 - the process is repeatative [sic] …”
- “You can capture all geometric properties on a single model.”
- “As long as the parts used are representative of industry parts, it should not matter.”
-

Table 4.54 *Results to Survey Question Number 32*

How does the CAD model compare in part count to other CAD models you have worked with in industry?

Answer	Response
In my experience, this model has the SAME number of parts as other models I have worked with	1
In my experience, this model has MORE number of parts as other models I have worked with	1
In my experience, this model has LESS number of parts as other models I have worked with	8

Table 4.55 *Results to Survey Question Number 33*

For the number of parts in the CAD model is there an appropriate amount of integrated GD&T?

Answer	Response
Yes	8
No, should be more	7
No, should be less	0
No, all of the parts should have integrated GD&T	2

Question: What could be improved and/or changed with the CAD model above?

- “Drive tooling and integrated product data Mgtmt.”
- “I think you have to start somewhere and the example is reasonable.”
- “For the specific example here, you may want to add embossed logos.”

Table 4.56 *Results to Survey Question Number 35*

Do you think the model above could be a benchmark CAD model used throughout a company, organization, or industry for testing?

Answer	Response
Yes	9
No	8

Table 4.57 *Results to Survey Question Number 38*

Do you think a potential benchmark model (not necessarily the model above) could be made and used for an industry?

Answer	Response
Yes	14
No	3

Table 4.58 *Results to Survey Question Number 41*

Do you think a potential benchmark model (not necessarily the model above) could be made and used for a company/organization?

Answer	Response
Yes	14
No	3

Table 4.59 *Results to Survey Question Number 44*

Do you think a potential benchmark model (not necessarily the model above) will be different for every company/organization because of diverse requirements that each company/organization may have?

Answer	Response
Yes	13
No	4

4.10. Chapter Summary

This chapter presented the results from the research conducted on interoperable and native CAD file formats. What was determined to be the most significant results were shown and any that were not can be found in Appendix C. The results for the survey were also given. The next chapter will discuss the themes and significance of the results found.

CHAPTER 5 DISCUSSION

5.1. Introduction

This chapter takes an in-depth look at the results of the previously mentioned research. The goal of this research is to determine capabilities of STEP AP203, JT, 3D PDF, and constraint-based native CAD file formats when compared to each other with regards to the preservation of information. The 3D PDF file format will be referenced as just PDF. The goal is not to determine the exact underlying causes of possible limitations or errors found in the results, but to determine overall relationships and themes. The survey is intended to determine how valid the benchmark model is for testing, possible changes that could be made to the model, and the model's possible application in industry.

5.2. Discussion of Interoperable File Formats

Three interoperable file formats, STEP, JT, and 3D PDF, have been analyzed according to the criteria listed in Section 3.3.3. The goal of this study is to determine what and how much information is preserved in the translation process. The criteria used to evaluate the file formats differ from previous studies currently available. The criteria are more comprehensive and the results more detailed.

5.2.1. Exporting Interoperable Formats

Not all of the CAD programs could export all of the interoperable file formats. Of the three interoperable file formats, STEP is the most widely implemented, simply based on the number of CAD programs that can export it. CATIA performed the best in file size reduction, when exporting models into STEP, reducing the model file size by 87 percent. However, the single STEP file CATIA exports only reduced the file size by 15 percent, the worst performer. NX performed the best, with the least absolute average change in volume at 0.004 percent. Inventor performed the worst when exporting STEP with a change of 13 percent. Pro/ENGINEER has the least absolute change in area with 0.07 percent. NX performed the worst, with an absolute change in area of 14 percent when exporting models to the STEP format. The tables corresponding to the discussion in this section can be found in sections 4.4.1, 4.5.1, and 4.6.1.

The JT file format is only supported by NX and Inventor for export. Inventor performs better than NX in file size reduction and absolute average change in area. NX performs better in absolute average change in volume. Refer to Tables 4.12, 4.13, and 4.14 in Chapter 4 for exact values.

The centroid results for exporting the STEP format provide NX has the lowest absolute change with 9 percent, and CATIA as the worst performer with 21 percent. NX has the best mean absolute standard deviation with 1.18E-06 percent while AI, not CATIA, has the worst standard deviation with 11 percent.

The JT file format performs better overall than the STEP format. AI out-performs NX with a 6.7 percent absolute change in the centroid. However, NX has a lower mean absolute deviation of 5.74E-06 percent.

The gap and curve translation error results show CATIA as the best performer for least average change in number of curves, with 4 percent. The number of curves are the maximum curvature (minimum radius of curvature) value, found by CADIQ. CATIA and Pro/ENGINEER tie for least average change in number of gaps with zero percent. All of the CAD programs have similar results for the average minimum radius of curvature around 0.56 mm. CATIA out-performs the rest of the CAD programs with the average maximum gap value of only 8.00E-05 mm.

For JT translation errors, Inventor performs better than NX for average change in number of curves and gaps, as well as average maximum gap value. NX only performs marginally better than Inventor for average minimum radius of curvature.

Pro/ENGINEER can export to a 3D PDF file, but the Adobe Acrobat X program can read the file but not export it to STEP. Therefore, there are no results for this translation other than the file size, which cannot be compared to other exported PDFs because there is none.

5.2.2. Importing Interoperable Formats

If a model is to be used for more than just visualization, then importing a model correctly is just as important as exporting. While file size can always be important in the case of importing it is not discussed. SolidWorks out-performs the other four CAD programs for absolute average change in area and volume for exporting STEP. The tables corresponding to the discussion in this section can be found in sections 4.4.1 and 4.6.1.

The JT file format is again only supported by two CAD programs, NX and Inventor for importing. NX out performs Inventor in both absolute average change in area and volume. NX import of JT only had an absolute average change in area of 0.01 percent and absolute average change in volume of 0.0005 percent.

CATIA and Inventor out-perform the rest of the CAD programs for translational error absolute change in number of curves with 17.86 percent and 17.04 percent respectively for STEP. While SolidWorks has an average of over 100 percent for absolute average change in number of curves, it out-performs the other CAD systems with only a 0.07 percent absolute average change in number of gaps. The average minimum Radius of Curvatures for the CAD programs are the same as exporting STEP. Inventor performs the best with the lowest maximum average gap value.

Inventor out-performs NX for importing JT in all of the CAD translation errors for absolute average change in number of curves, absolute average change in number of gaps, minimum average radius of curvature, and maximum average gap value.

5.2.3. CAD Translation to Interoperable Format

Each CAD program has different capabilities for importing and exporting the interoperable file formats. The STEP format can be imported and exported from each of the five CAD programs, more than JT and PDF combined. PDF has been implemented into Pro/ENGINEER with the capability of exporting only.

File size is an important part of interoperable file formats because the smaller the file size the easier it is to transfer the model compared to the original. All three interoperable file formats are within 2 percent of each other in the reduction of file size relative to the original native CAD file. The mean absolute deviation for each of the formats is also within 2 percent of each other at 18 percent, 19 percent, and 20 percent. The deviation is large enough that no format stands out since one format could perform better than the other at different times. The tables corresponding to the discussion in this section can be found in sections 4.4.1, 4.4.2, 4.6.1, and 4.6.2.

For the absolute average change in volume, PDF performs the best of the three formats with an average of only 2 percent change. All three file formats are within 7 percent of each other. PDF also had the least mean absolute deviation at 4 percent. The other file formats had 7 percent and 18 percent. The file formats are close enough together with large enough deviations that it is difficult to say that PDF is the best performer. The other formats could possibly beat PDF because of the large deviations. However, the 3D PDF files were tested in CADIQ as STEP files, since CADIQ cannot read native PDF files. The PDF results went through one more process than the other file formats. This additional process increases the chances of errors to occur and precision to decrease. Based on the results found this does not appear to be the case in the context of change in volume.

The results for the absolute average change in area reveal a greater discrepancy between the file formats than for the previous criteria. 3D PDF performs the best with only an absolute average change in area of 2 percent. The three file formats differ by 9 percent. The absolute mean deviations for STEP and JT are large enough that the formats could get as small a change in area as 3D PDF. Again, 3D PDF performs better than

STEP and JT even through it is translated though an additional process allowing for a greater chance of possible errors and decrease in precision.

The change in number of gaps and curves found in the models continues the trend of increasing disparity between the three file formats. In both cases STEP performs better with 3D PDF only 6 percent higher for gaps and 4 percent higher for curves. JT is 22 percent higher than 3D PDF in gaps and 12 percent higher in curves. The mean absolute deviation is very large for JT at 46 percent for gaps and 38 percent for curves. The mean absolute deviation for the JT format is significantly larger than other criteria results and other formats, suggesting that the JT format's weakness is translation of gaps and curves. The larger deviation suggests that the JT format is much more inconsistent than the other file formats.

The average maximum value for the high-curvature curves and the mean absolute deviation are negligibly the same for all three formats, with only a maximum average difference of 12 percent. The difference for the mean absolute deviation is only 7 percent. For the average maximum value for the gaps STEP is the best performer. JT and PDF differ by more than 150 percent from STEP for the average and deviation of the maximum gap values. The deviations for all three formats are significantly lower than the previous criteria. STEP has the lowest deviation and is by far the best performer overall for the average maximum gap values.

5.2.4. Interoperable Format Translation to CAD

Each of the interoperable file formats were translated back into all of the CAD programs and then analyzed. Adobe Acrobat X nor any of the CAD programs have the capability of directly translating the PDF format to a native CAD format. As a result there were no files to analyze and no results.

File size is important for interoperable file formats because it makes it easier to send and receive the files. File size is one of the advantages interoperable formats have over native CAD formats. The results for all the format's file sizes can be found in section 4.4.1. The tables corresponding to the discussion in this section can be found in sections 4.4.1 and 4.6.1.

When the interoperable formats are imported into the five CAD programs, JT performs better than STEP in absolute average change in volume, with 0.65 percent and 3.89 percent, respectively. The JT format also out-performs STEP for the mean absolute deviation. JT has a very low deviation of only 1.11 percent compared to STEP's 7.28 percent. The absolute average change in area is the same result as the volume with JT performing better than STEP. There is a greater disparity in the change in area than there is in volume. JT performs significantly better than STEP in the absolute average change in volume and area.

While JT out-performs STEP with change in volume and area, STEP exceedingly out-performs JT in most of the evaluation error criteria. STEP performs the best in absolute average change in number of gaps with 15 percent versus JT's 45 percent. The disparity increases with the absolute average change in number of curves, STEP changing 32 percent and JT changing 112 percent. STEP and JT are very similar with the minimum average radius of curvature of 0.58 mm and 0.6 mm respectively. STEP out-performs JT in maximum average gap value with 4.E-04 mm to JT's 7 mm.

5.2.5. Summary of Interoperable File Formats

Based on the results of the analysis criteria no CAD program can out-perform the others when importing or exporting any of the interoperable file formats. Conclusions can only be made on possible CAD programs to choose for each of the interoperable file formats if individual criteria or similar criteria are selected.

Like the CAD programs, none of the three interoperable file formats out-performs the others in all the criteria. These results should not be surprising as they follow with Ball (2007), "there is no one lightweight format that stands out as ideal in all scenarios." However, PDF performs the best in several criteria even though it is the least implemented by any of the five CAD programs and the newest of the three formats.

The more expansive analysis and results do not lead to a dominant file format but can help determine which file format may be better for a company, organization, or individual. With results from five industry leading CAD packages and more analysis criteria small, to medium size companies should be able to make a better informed decision if interoperability is currently a problem for them.

5.3. Comparison of Native CAD and Interoperable File Formats

The three interoperable file formats discussed in the previous section are imported and exported using the five CAD programs, CATIA V5, Autodesk Inventor 2012, SolidWorks 2010, Pro/ENGINEER 5.0, and NX 7.5. Along with importing and exporting the three interoperable file formats, the CAD programs have the capabilities to import and export some of their disparate programs native file formats. Not all five of the CAD programs have the ability to import or export the other CAD programs native file formats. The CAD programs' capabilities can be seen in Table 3.1, shown previously.

CATIA V5 does not have the capability to import or export any other CAD program's native file format. Pro/ENGINEER does not have the ability to export any other CAD programs native file format but can import.

The three interoperable file formats can be used to translate CAD models between disparate programs. Along with the ability to import and export interoperable file formats, some CAD programs can import and export other CAD programs native file formats directly. This can be a valuable functionality in a CAD program as it is one less step in the translation process, for an error to occur or values to lose precision. The direct translation process, in theory, has potential to be a better way to transfer CAD models between disparate CAD programs. This is also assuming that a company would intentionally integrate the ability to import or export a competitor's product.

One of the advantages of the three interoperable file formats is the smaller file size compared to the native CAD formats. This allows for greater file mobility. However, transferring native file formats directly between CAD programs would skip a step compared to using interoperable formats, but also skips on the smaller file size.

The comparison will be made by relating what would be the end result of a translation process. This means that only the results for an interoperable format translation process that ends with a CAD program will be used. Therefore, only STEP and JT can be compared to the CAD to CAD native translation process because PDF cannot be translated directly into a CAD program by another CAD program or Adobe Acrobat X.

To ensure a comprehensive comparison of all available file formats, the results from the native CAD translation directly to another native CAD file format can be compared to the interoperable equivalent. For example, Inventor can import native CATIA. The equivalent inoperable file path would be CATIA to interoperable format to Inventor. The only possible path using any of the three interoperable formats would be CATIA to STEP to Inventor.

The combinations of comparisons results in all the interoperable equivalent translation paths only include STEP, except for Inventor imports NX also has JT as a possible intermediate. Using the results in Sections 4.4.3, 4.5.3, and 4.6.3, some of the native CAD-to-CAD translations out-perform their STEP and JT equivalents. When the native SolidWorks model is imported into Inventor and NX, both translations out-perform any other equivalents in all criteria. Other native CAD to CAD translations out-perform their STEP or JT equivalents with some of the criteria. This shows that some of the CAD vendors have taken direct translation seriously and made a direct native translation that is better than the interoperable equivalents with at least one criteria.

5.4. Discussion of Survey

The survey’s main goal is to be a form of validation, to determine how appropriate the benchmark model is for this research and for possible use in industry testing. The survey revealed several important issues with the benchmark model.

5.4.1. Benchmark Assembly

There is no dominant theme regarding assemblies from the survey. The survey suggests that the BM assembly is adequate in complexity. The survey also suggests that the BM assembly needs to be more complex with more subassemblies. One possible theme is that the BM assembly does not surpass what the participants feel would be a good benchmark. All of the participants who said the model should not change only said that it is adequate. This means in order to be safe and have a conclusive benchmark model there needs to be more sub-assemblies with more complexity regarding how the parts fit together.

Six of the seventeen participants said that the number of sub-assemblies does not matter. The number of sub-assemblies does not matter because it is more critical that the associations, relationships, and conversions are properly addressed as long as there is at least one sub-assembly (Participants 12 & 16). Rating a model's complexity by the number of assemblies is outdated, complexity is partially defined by the number of parts or sub-assemblies, but more important are the number of variations and the restrictions of those variations (Participant 5). The theme that the number of sub-assemblies does not matter is established but not dominant because only 35 percent of the participants felt this way.

5.4.2. Benchmark Parts

Based on the survey, the benchmark model used in this study has a sufficient number of parts but has fewer parts than those found in industry. The participants first impressions were that nine of them agreed that the BM had a good number of parts, while only four of them said that it has too few number of parts. However, 53 percent of the participants said that the number of parts does not matter. In a follow up question later in the survey, the participants are asked again if the number of parts in a BM matters and 59 percent said yes. Six participants answered the two questions consistently and four participants answered the questions inconsistently. These answers suggest that the participants are not sure if the number of parts in a BM should matter. The participants that gave conflicting answers to whether the number of parts in a BM matters did not give direct, specific support for either answer.

Most participants said that the number of parts in a benchmark model should matter because of scalability. Participant 10 said that scalability is a big use for some file formats, and weird things start to happen with massively large data sets. Participants 6 and 9 said that the number of parts matter if that is what is being tested.

The number of parts in a benchmark model should not matter because the number of parts does not qualify, as a benchmark. The complexity and types of parts is more important. Once enough complexity with the parts has been reached and covered all of the types, the rest is just repetitive and only needs to be taken into account if testing memory and hardware (Participants 1, 2, & 8). The participants did not specify what they meant by part types but other answers suggest that the participants are possibly talking about CAD features (i.e.: fillets, ribs, lofts, etc.), geometry entities defined in a standard (i.e.: trimmed_curve and uniform_curve for STEP), or specific part types a company uses (i.e.: standard fastener, proprietary engine parts, or a simple safety plaque).

The participants' answers to the survey show, theme of low complexity regarding the benchmark model. A significant portion of the participants, 76 percent of them, said that most complex parts in the BM were not complex enough. The participants think the BM should have more complex parts consisting of composite materials, free-form and organic surfaces. This is a valid point but the aim of this study did not include free-form, organic surfaces. However, 76 percent of the participants agreed that the number of geometrically complex parts matters in a BM. The number of geometrically complex parts matter because it can show "the flexibility and strength of a CAD product" (Participant 3). Also, production models are complex and complex parts test the manufacturing solutions (Participants 15 & 17). The four participants who said that the number of geometrically complex parts does not matter suggest in their written response that the number actually can matter but not necessarily the quantity. "Make sure you have enough to adequately exercise all of the entity types in the STEP or JT standard" (Participant 6). "As long as it is representative it should not matter" (Participant 12). The

BM needs “to ensure all use cases/types are comprehended” (Participant 16). These answers suggest that the number of geometrically complex parts matters up to a point where all use cases and types are covered, after that, quantity no longer matters.

5.4.3. Benchmark PMI

The PMI in the BM used in this study is appropriate but the model could have more. The participants were split regarding the PMI in the BM. 47 percent said that the BM currently has an appropriate amount of PMI, while 41 percent said that there should be more PMI. The participants felt that the amount and content of the PMI is adequate. Improvements could be made including having assembly level PMI, weld information, and covering everything from a GD&T manual (Participants 6, 10, & 12). Similar to the previous topic of assemblies, the PMI is adequate. In order to have a conclusive benchmark model, the model used in this study needs to be improved upon with more PMI and cover all possible use cases.

5.4.4. Benchmark in Industry

While the benchmark model used in this study is adequate in many aspects but should be improved upon, 53 percent of participants said that the model could be used as a benchmark in a company, organization, or industry, while 47 percent said it could not. However, when the participants were asked if a BM model, not necessarily the one used in this study, could be made and used in industry, 82 percent said yes. When participants were asked the same questions but if a benchmark model could be used in a company/organization, 82 percent said yes. Participants echoed what was explained before about how the benchmark model needs more parts, PMI, and complexity. Those that said the model could be used as a benchmark explained the model represented a minimum of requirements but could be improved upon.

A majority of participants, 82 percent, agreed that a benchmark model could be used in an industry, one that covers all possible use cases within that industry. The participants that said a single benchmark model could not be used for an industry, suggested that the requirements for an entire industry are too heterogeneous and covering all use cases in one model is not possible (Participants 2 & 17). The same majority of participants agreed that a benchmark model could be used for a company or organization. The participants explained that this would be easier than defining a benchmark for industry, as most companies have established standards and requirements.

When the participants were asked if a potential benchmark model would be different for every company or organization due to diverse requirements, 76 percent said yes. This contradicts the answers the participants gave in a previous question, that a single model could be used in an industry as a benchmark. The conclusions of both questions could suggest that a single benchmark model could be used in an industry but that it would need to be customized to an extent for use across multiple companies of organizations.

5.4.5. Survey Summary

Based on the answers from the survey, the number of parts only matters if that is what is being tested. If the goal of the test is to determine the quantity of parts a CAD product or translation process can handle, then yes, the number of parts matters, otherwise no. However, the number of geometrically complex parts matters but only to a point. When all of the possible use cases and entity types have been covered, then the number of geometrically complex parts does not matter unless that is what you are testing.

The ideal BM, based on the results of the survey, that could be used regardless of the goal of the test, is one consisting of multiple sub-assemblies, thousands of parts, and have PMI that covers all possible use cases for a company or industry. The thousands of parts should be complex enough to cover all use cases and entity types for all possible translation processes. After all of the use cases and entity types are covered the rest of the parts do not need to be as complex.

The survey suggests that a benchmark model can be made for an industry and companies or organizations within that industry. The BM used within an industry may need to be further customized to capture all of the use cases and requirements used in a company or organization.

Based on how the participants answered the free response questions, if the sample size were increased significantly, similar results would most likely be found. This is due to the fact that many of the participants gave varying answers to questions that were asked twice but phrased differently in the survey. Another reason the survey results suggest that a similar outcome will be found with an increase in sample size is when the free response answers are read it appears as if many participants had not given much in-depth thought into a benchmark model. The participants appeared to have very broad opinions.

5.5. Conclusions

Computer Aided Design and Computer Aided Engineering are here to stay. It has become an integral part of how many companies spanning many industries do business. One of the issues more and more companies are facing in the problem of interoperability. “[Interoperability] is essential to the productivity and competitiveness of many industries because efficient design and manufacturing require the coordination of many different participants and processes that rely on a digital representation of the product” (Brunnermeier, 1999, p. ES-1). Interoperability causes problems in the design process leading to significant economic inefficiencies at an estimated cost of $1 billion in the U.S. automotive industry during 1999. These interoperability costs are predominantly due to supporting multiple CAD/CAx systems and fixing errors in when data is exchanged between desperate software systems. (Brunnermeier, 1999, p. 5-1).

The goal of this study was to determine how STEP AP203, JT, 3D PDF, and five constraint-based native CAD file formats’ capabilities compare to each other with regards to preservation of information. A benchmark model was used for the analysis allow for a better analysis of the translation process due to the same model being used in each CAD system.

Based on the results from the analysis of the evaluation criteria there is no overall clear cut better performer that is significantly better than the other two formats. This goes along with what Ball said in 2007, “there is no one lightweight format that stands out as ideal in all scenarios.” However, PDF performs the best in several criteria even though it is the least implemented by any of the five CAD programs and the newest of the three formats.

If what software can read or write, a file format is an indication of how widely accepted a file format is, then as with all previous research, the results of this study show that STEP is the most widely accepted/implemented interoperable file format. However, even though STEP is the most widely accepted/implemented file format it does not out-perform the other two file formats in all the criteria.

The answers from the survey show the number of parts only matters if that is what is being tested. If the goal of the test is to determine the quantity of parts a CAD product or translation process can handle, then yes, the number of parts matters, otherwise no. However, the number of geometrically complex parts matters but only to a point. When all of the possible use cases and entity types have been covered then the number of geometrically complex parts does not matter unless that is what you are testing. The benchmark model used in this study is a good start but needs to be improved upon in many ways.

5.6. Recommendations for Future Research

The CAD industry and the industries that use CAD have been around for many years and it looks like those industries are not going anywhere anytime soon. Research on interoperability and especially file formats needs to continually be completed because of the ever changing CAD programs and interoperable file formats. Through this research interoperable file formats will also be able to continually improve.

Completing a study including multiple file formats and multiple CAD systems using a model built from scratch in each CAD system is very tedious and very time consuming. However, the more a study is all encompassing the better chance it has in driving forward interoperability solutions. Future studies should include more analysis criteria with at least more than one CAD analysis tool. The studies should include performing specific file translation multiple times to see if the results are repeatable.

The survey revealed that a future benchmark model needs to improve upon the one used in this study. The survey is also something that can be improved upon. The biggest issue is the length of the survey. Many people did not finish the survey and an unknown amount did not start simply because they knew it would take up too much of their time. Future surveys should include a second round to adjust questions or other issues. An issue that may prove to be difficult to get around is participants not directly answering the written response questions, but rather answering the question with something else in the survey they feel needs to be addressed more urgently. One last issue is how to allow the user to interact with a CAD model while not limiting the survey in anyway.

The survey contained several 3D PDFs to allow the participants to interact with the models, without giving them the actual CAD files in an interoperable or native format. The 3D PDFs used in the survey were scaled down in presentation quality to reduce the size of the file. Time was believed to be a significant factor in how many experts completed the survey. Reducing the time it took for the models to load in the survey was crucial. Time most likely played a factor in how many participants finished the survey because 28 participants started it but only 17 completed the entire survey.

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APPENDICES

Appendix A. IRB Approval and Participant Consent Forms

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	NATHAN HARTMAN KNOY 311
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	11/17/2011
Committee Action:	Approval
IRB Action Date	11/15/2011
IRB Protocol #	1110011433
Study Title	An Analysis of STEP, JT, and PDF Translation Between Constraint Based CAD Systems with a Benchmark Model
Expiration Date	11/14/2012

Following review by the Institutional Review Board (IRB), the above-referenced protocol has been approved. This approval permits you to recruit subjects up to the number indicated on the application form and to conduct the research as it is approved. The IRB-stamped and dated consent, assent, and/or information form(s) approved for this protocol are enclosed. Please make copies from these document(s) both for subjects to sign should they choose to enroll in your study and for subjects to keep for their records. Information forms should not be signed. Researchers should keep all consent/assent forms for a period no less than three (3) years following closure of the protocol.

Revisions/Amendments: If you wish to change any aspect of this study, please submit the requested changes to the IRB using the appropriate form. IRB approval must be obtained before implementing any changes unless the change is to remove an immediate hazard to subjects in which case the IRB should be immediately informed following the change.

Continuing Review: It is the Principal Investigator's responsibility to obtain continuing review and approval for this protocol prior to the expiration date noted above. Please allow sufficient time for continued review and approval. No research activity of any sort may continue beyond the expiration date. Failure to receive approval for continuation before the expiration date will result in the approval's expiration on the expiration date. Data collected following the expiration date is unapproved research and cannot be used for research purposes including reporting or publishing as research data.

Unanticipated Problems/Adverse Events: Researchers must report unanticipated problems and/or adverse events to the IRB. If the problem/adverse event is serious, or is expected but occurs with unexpected severity or frequency, or the problem/even is unanticipated, it must be reported to the IRB within 48 hours of learning of the event and a written report submitted within five (5) business days. All other problems/events should be reported at the time of Continuing Review.

We wish you good luck with your work. Please retain copy of this letter for your records.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

RESEARCH PARTICIPANT INFORMATION SHEET
An Analysis of STEP, JT, and PDF Translation Between Constraint Based CAD Systems with a Benchmark Model
Prof. Nathan W. Hartman
Purdue University
Computer Graphics Technology

Purpose of Research
This research is focused on analyzing the ability of STEP AP 203 edition 2, JT, and PDF to translate the necessary and correct information. Part of this research is using a benchmark model which was made to be comparable to an engineering CAD model that could be found in industry. To accomplish this goal, I would appreciate if you or someone else you know who has knowledge and experience with CAD models could fill out a short online survey relative to this topic. Please forward this survey to anyone in your organization who has knowledge of CAD models. The survey will consist of questions designed to get your impressions of a CAD model and how it compares to CAD models you have interacted with in industry. Please click the following link which will take you to Purdue University's hosted survey site which has been constructed and administered by myself to collect information to identify specific strengths and weaknesses of a CAD model and how it compares to 3D CAD models you have interacted with in industry. The goal of this survey is to determine if the specific CAD model is a good representation of what could be found in industry and if not how it could be improved for a more accurate representation.

Specific Procedures
Take a short survey in which no identifying information will be collected about you, or your organization.

Duration of Participation
Take one survey one time. The survey will last approximately 25-30 minutes.

Risks
The potential risk associated with the survey and the research is no greater than every day activities.

Benefits
Although there are no direct benefits to the participation, there are no risks greater than that found in everyday life. The benefits in the case of this survey are attributed to the furthering of research and thus in the best interest of the survey's participants who share an interest in seeing research related to 3D CAD progress.

Compensation
N/A

Confidentiality
The project's research records may be reviewed by Dillon Mckenzie-Veal, Prof. Nathan W. Hartman, Ed.D, and by departments at Purdue University responsible for regulatory and research oversight.

Voluntary Nature of Participation
A minimum of 10 years of experience working with computer aided design models is required to take the survey. You do not have to participate in this research project. If you agree to participate you can

withdraw your participation at any time without penalty. All participants must be age 18 years of age or older.

Contact Information:
If you have any questions about this research project, you can contact Nathan W. Hartman, Ed.D at 765.496.6104 or Dillon McKenzie-Veal at 765.496.6104. If you have concerns about the treatment of research participants, you can contact the Institutional Review Board at Purdue University, Ernest C. Young Hall, Room 1032, 155 S. Grant St., West Lafayette, IN 47907-2114. The phone number for the Board is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent
I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above.

I AGREE AND WISH TO TAKE THE SURVEY   I DO NOT AGREE TO PARTICIPATE

Appendix B. Survey Questions

Are you 18 years of age or older?

* Yes

* No

>If no is selected, then skip to end of survey.

Q1

Select the option below that best describes your company's industry sector:

* Aerospace
* Automotive
* Defense
* Consumer Products
* Industrial Equipment
* Medical
* Other

Q2

Please select the highest degree you have obtained from the list below:

* High School
* Associates Degree
* Bachelor's Degree
* Master's Degree
* Doctorate of Philosophy

Q3 (if Q2 = Bachelor’s degree)

What area is your bachelor’s degree in?

* Computer Science
* Computer Graphics
* Engineering
* Design
* Other: (please specify) _____________

Q4 (if Q2 = Master’s degree)

What area is your master’s degree in?

* Computer Science
* Computer Graphics
* Engineering
* Design
* Other: (please specify) _____________

Q5 (if Q2 = Doctorate of Philosophy)

What area is your Ph.D. in?

* Computer Science
* Computer Graphics
* Engineering
* Design
* Other: (please specify) _____________

Q6

How many years of experience do you have working with CAD models? (i.e. making, modifying, or viewing)

* Less than 1 year
* 1-5 years
* 6-10 years
* 10+

Q7 (if Q6 = 10+)

If you have 10+ years of experience with CAD models would your peers consider you an expert in the domain of CAD models?

* Yes
* No

Q8 (if Q7 = Yes)

Why do you think your peers would consider you an expert in the domain of CAD models?

[Area to freely write]

Q9 (if Q7 = No)

Why do you think your peers would not consider you an expert in the domain of CAD models?

[Area to freely write]

Q10

Do you have any certifications related to CAD modeling?

* Yes
* No

Q11 (if Q10 = Yes)

If you would like you can specify the certification(s): (1 per line)

[Area to freely write]

Q12

Do you belong to any consortiums or societies related to CAD modeling?

* No
* Yes

Q13

Have you published an article or given a professional presentation relating to the use of CAD tools?

* Yes
* No

Q14 (if Q13 = Yes)

If you would like, you can specify the subject matter of the published work or professional presentation:(1 per line)

[Area to freely write]

This part of the survey will present you with some information on a CAD model. Please answer the following questions with your own assessment of the information given. There is no right or wrong answer, just your opinion.

The CAD model below is currently being proposed as a benchmark model in various CAD systems, because there exists no in-depth, multilevel comparison of the neutral file formats and various individual proprietary CAD packages at the geometry kernel level. This research paper could answer how various major CAD programs read/write ability of neutral file formats compare to each other. In order to properly assess the capabilities of each CAD program, a benchmark model should be used.

The idea behind the benchmark model is to use the same exact model created natively in each CAD program so that consistency can identify possible errors. A benchmark model was created because no research has used the same model across the translation process, nor could a potential benchmark parametric CAD model be found publically.

This research will help answer what a benchmark CAD model could be comprised of, with the complexities and integrated product definition data needed to accurately represent today's sophisticated products. To better understand the capabilities of each CAD program, the capabilities and limitations of the neutral file formats being used must be understood.

This research differs from that of CAx-IF in PDES and ProSTEP in that more CAD programs and file formats will be used in testing as well as a single master model created natively in all of the CAD programs. The criteria involved in the research will also be more comprehensive than previous studies. The results will be available to the public and not restricted to members only.

Part of your assessment will be to determine if you believe the model could or could not be a benchmark model. General Info on the CAD model:

- The model file size is 5 MB – 15 MB depending on the CAD system.
- 1 Assembly.
- 1 Sub-Assembly.
- 29 Parts total.
- 4 of the parts are standard parts from the respective CAD systems Standard Parts Library.
- 4 different materials have been applied with associated material properties.
- 6 different custom colors have been applied.
- The PMI & GD&T has been integrated and applied to the 3 parts in the scissor sub-assembly.
- All of the parts in the assemblies and sub-assemblies are fully constrained.

The following paragraphs will provide links to 3D PDFs. You only need Adobe Acrobat Reader (free) to view each PDF. Each link will take approximately 10 seconds to load. The link will open a new browsing window if your web browser is configured to do so with PDFs. If not, the link will open in a separate Acrobat Reader window. [“(free)” in the paragraph above will be a link to Adobe to download Adobe Acrobat Reader]

*To manipulate the following 3D PDFs click on the model or part. Use the middle mouse button to rotate. Use the mouse scroll wheel to zoom. You can change the lighting and the background color to your liking.

This is a 3D PDF* of the model assembly:
[Link to corresponding 3D PDF]

This is a 3D PDF* of an alternate view of the model assembly:
[Link to corresponding 3D PDF]

This is a 3D PDF* of part 1 of the Scissor Sub-Assembly:
[Link to corresponding 3D PDF]

This is a 3D PDF* of part 2 of the Scissor Sub-Assembly:
[Link to corresponding 3D PDF]

This is a 3D PDF* of part 3 of the Scissor Sub-Assembly:
[Link to corresponding 3D PDF]

This is a 3D PDF* of one of the more complex parts in the model:
[Link to corresponding 3D PDF]

This is a 3D PDF* of another complex part in the model:
[Link to corresponding 3D PDF]

This is a 3D PDF* of another complex part in the model:
[Link to corresponding 3D PDF]

Q15

What is your first impression of the model in terms of assembly complexity and number of parts? (Please mark all that apply)

* Good assembly complexity.
* Good number of parts.
* Too simple assembly.
* Too few number of parts.

Q16

Explanation of your first impression of the model in terms of assembly complexity and number of parts:

[Area to freely write]

Q17

What is your first impression of the model in terms of individual part complexity?

[Area to freely write]

Q18

What is your first impression of the model in terms of geometric dimensioning and tolerancing (GD&T)?

[Area to freely write]

Q19

How does the model above in terms of number of parts relate to models you have interacted with in industry?

* High part count
* Medium part count (about in the middle)
* Low part count
* I do not think the number of parts matters in having a benchmark model for testing

Q20 (if Q19 = "I do not think the number…")

Why do you think the number of parts does not matter in having a benchmark model for testing?

[Area to freely write]

Q21

When comparing this model to models you have interacted with in industry, this model should:

* have more sub-assemblies.
* stay with the one sub-assembly it has.
* have no sub-assemblies.
* the number of sub-assemblies does not matter.

Q22 (if Q21 = "the number of sub-assemblies does not matter")

Why do you think the number of sub-assemblies does not matter in having a benchmark model for testing?

[Area to freely write]

Q23

In your opinion, are the Corkscrew, Keyring, and Saw parts (shown above) geometrically complex?

* Yes
* No
* Too little information present.

Q24 (if Q23 = Too little information present)

If there is too little information present, please explain:

[Area to freely write]

Q25

Does the number of geometrically complex parts in a potential benchmark assembly model matter? (Please explain)

* Yes
* No

Q26 (if Q25 = Yes)

Why does the number of geometrically complex parts in a potential benchmark assembly model matter?

[Area to freely write]

Q27 (if Q25 = No)

Why does the number of geometrically complex parts in a potential benchmark assembly model NOT matter?

[Area to freely write]

Q28

Does the potential benchmark assembly model above have a sufficient number of geometrically complex parts when comparing it to a model you might find in industry?

* Yes
* No, should be more
* No, should be less

Q29

Does the number of parts in a potential benchmark model matter? (Please explain)

* Yes
* No

Q30 (if Q29 = Yes)

Why does the number of parts in a potential benchmark model matter?

[Area to freely write]

Q31 (if Q29 = No)

Why does the number of parts in a potential benchmark model NOT matter?

[Area to freely write]

Q32

How does the CAD model compare in part count to other CAD models you have worked with in industry?

* In my experience, this model has the SAME number of parts as other models I have worked with.
* In my experience, this model has MORE number of parts as other models I have worked with.
* In my experience, this model has LESS number of parts as other models I have worked with.

Q33

For the number of parts in the CAD model is there an appropriate amount of integrated GD&T?

* Yes
* No, should be more
* No, should be less
* No, all of the parts should have integrated GD&T

Q34

What could be improved and/or changed with the CAD model above?

[Area to freely write]

Q35

Do you think the model above could be a benchmark CAD model used throughout a company, organization, or industry for testing?

* Yes
* No

Q36 (if Q35 = Yes)

Why do you think the model above could be a benchmark CAD model used throughout a company, organization, or industry for testing?

[Area to freely write]

Q37 (if Q35 = No)

Why do you think the model above could NOT be a benchmark CAD model used throughout a company, organization, or industry for testing?

[Area to freely write]

Q38

Do you think a potential benchmark model (not necessarily the model above) could be made and used for an industry?

* Yes
* No

Q39 (if Q38 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could be made and used for an industry?

[Area to freely write]

Q40 (if Q38 = No)

Why do you think a potential benchmark model (not necessarily the model above) could NOT be made and used for an industry?

[Area to freely write]

Q41

Do you think a potential benchmark model (not necessarily the model above) could be made and used for a company/organization?

* Yes
* No

Q42 (if Q41 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could be made and used for a company/organization?

[Area to freely write]

Q43 (if Q41 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could NOT be made and used for a company/organization?

[Area to freely write]

Q44

Do you think a potential benchmark model (not necessarily the model above) will be different for every company/organization because of diverse requirements that each company/organization may have? (Please explain)

* Yes
* No

Q45 (if Q44 = No)

Why do you think a potential benchmark model (not necessarily the model above) will NOT be different for every company/organization because of diverse requirements that each company/organization may have?

[Area to freely write]

Q46

Any other thoughts or ideas about the CAD model shown above?

[Area to freely write]

Appendix C. Results for Short Answer Survey Questions

Individual answers, for questions that participants were allowed to write freely, are separated by bullet point. The results are displayed as they were answered with no changes made to spelling, grammar, or formatting.

Q8 (if Q7 = Yes)
Why do you think your peers would consider you an expert in the domain of CAD models?

- Because of over 20 years of modeling and 40 + years in design, I know the capabilities and limitations of CAD tools that I have used over the years.
- Because I constantly recieve referrals of problem parts and questions on modelling techniques from my peers
- Yes I work for Siemens PLM and have been certified in NX. I have also worked in industry
- Used multiple CAD packages and traing industry professionals and students in high school, middle school, community college and higher education.
- Background and extensive experience in applicaiton, pratice and numerical theory
- I have been working on the devleopment of data excahnge products for more than 15 years.
- I have been actively involved in the evaluation, development, deployment, operations and support of a number of CAD systems. I have also implemented a number of automations that automatically build CAD models with the associated PMI.
- I have 19 years experience working with CAD and 3D visualization models.
- Worked developing geometry and topology algorithms in Parasolid and ACIS. Also developed translators for commercial CAD products. Developed the STEP and IGES b-rep standards.
- Math knowledge. Knowledge of NURBS algorithms.

- 30 years working with product design and manufacturing companies starting with CADAM then several small Mfg software packages. Moved to Unigraphics in the mid 80's which became NX after many iterations
- 20 years experience in CAD data exchange involve knowhow in various CAD systems (mainly in geometric model of CAD systems)

Q9 (if Q7 = No)

Why do you think your peers would not consider you an expert in the domain of CAD models?

- Rather managing CAD than creating it
- Although I am dealing with CAD modeling and design due to the nature of my job (IT department that deals with the conversion of CAD models to our software) the amount of expertise that I have acquired is limited to a small part of the CAD process.

Q11 (if Q10 = Yes)

If you would like you can specify the certification(s): (1 per line)

- Siemen Cad Certification
- Autodesk Inventor AIC
- Autodesk Inventor Associate
- NX5 basics, from Siemens PLM
- Certifcates of completion from Unigraphics training classes in Design and Mfg

Q14 (if Q13 = Yes)

If you would like, you can specify the subject matter of the published work or professional presentation:(1 per line)

- CAD relational design
- CAD data translation
- CAD data migration
- CAD data interoperability

- CAD data intelligence
- Explicit Design of Advanced Composite Structure
- PLM
- PDM
- Educational applications of CAD
- CAD Model Mangement
- CAD Construction Methods
- STEP
- IGES
- JT
- Numerical Methods
- Tolerance analysis using JT data.
- LOTAR
- Product and customer facing prestations in the area of data exchange.
- JT on the Shop Floor
- Computers and Structures
- Desktop Engineering
- Mechanical Engineering
- Numerous industry conferences
- User group presentations on Mfg using Unigraphics / NX
- 3D Interoperability
- Collaboration
- Extending 3D Workflows/Maodel Based Enterprise
- Value Chain Integration
- COM/FOX enables high end applications of JT and PLMXML at Daimler (PLM World 2008)
- COM/FOX enables high end applications of JT and PLMXML (ProSTEP Symposium 2010)

Q16

Explanation of your first impression of the model in terms of assembly complexity and number of parts:

- Ok as an example, but not complex enough for large industry such as auto or aerospace. The lack of a link between PMI and product definition was also evident.
- Looks pretty good
- This would be a good test for mid-range CAD systems, but not for high end systems
- The model assembly seem appropriate for the product it represented.
- We3 deal with assemblies of > 1000
- Resonable model. Missing complex curvature surfaces used in aerospace and automotive (ie. airfoil or car body) Good start with PMI. Could add some complexity to annotations.
- Considering the viewing usage only, the 3D pdf tool is good. There is the possibility to have a lot of parts in a complex assembly.
- Good
- The case would be considered simple in terms of number of parts, but reasonable example for comparision.
- i don't think there are enough sub assemblies to test whether assembly and part placements are correct when converted to a derivative format, such as 3D PDF or JT. I would think each scenario should be tested, including:
    - 1. Statically constrained
    - 2. Dynamically constrained via variable or function
    - 3. Absolutely positioned in space
- It is not overly complex. It is quite detailed without being heavy.
- It looks like a reasonable number of parts for a benchmark.
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.

- The assembly is too simple. Typical customer assemblies are larget with more complex parts.
- nice assembly presenting the opportunity for simple positioning of parts
- Not sure I understand why you have separated the model into several PDF files. Why is GD&T not associated with views and geometry?
- adequate complexity and number of parts

Q17

What is your first impression of the model in terms of individual part complexity?

- pretty basic. I would see a need for more than one benchmark assy. one like this and a much larger complex assy of much more complex parts such as an airplane wing or a body section of an auto. Non ruled surfaces and complex realtionships to PMI are the major blockages in data intelligence and consumption of it.
- I would have liked to see more tappered fillets and shallow angle fillets - but it is a good start. Possibly a point on the corkscrew?
- Simple
- The model parts seem appropriate for the product it represented.
- low, regular geometry, not many free-form surfaces
- Simple parts are good. The knife may not represent all the entity types you need for a benchmark.
- I like the simple parts in the blades that have surfaces like the saw blade
- If a benchmark part is too big or complex, it becomes difficult to use.
- In a benchmark standard model you'd like to have at least one of every major entity type supported by STEP. Output your model then compare the STEP output to see how many types are represented. Do this with more than one CAD tool
- The model was complex enough for the test.
- good
- The parts give enough geometry complexity to make it a reasonable test example.
- too simple. No textured surfaces, no artwork, no composite materials, no molded / organically shaped pieces.

- Each part has the geometry that it should. No more, no less than necessary
- The part complexity has good potential for a range of features.
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.
- Parts are simple. There aren't any complex surfaces.
- These are pretty much all stamped parts, no complex (corkscrew is interesting but most systems do that easily now, this one is actually no so good) surfaces or difficult part to part orientations.
- nothing terribly complex.
- low complexity

Q18

What is your first impression of the model in terms of geometric dimensioning and tolerancing (GD&T)?

- Pretty basic. The lack of links between features, parts and PMI is a major issue with manufacturing consumption of product definition. As a comment on the selection below, I would say that the issue is more about the complexity of the parts than the size (quantity).
- OK - but not my field
- look typical
- They seem valid
- none
- Looks like a number of the some of the basics are there. Just make sure you cover everything from a GD&T manual.
- There is no possibility to simulate the behavior of the part by the tolerances defined before. There are some viewing tools which enables the user to do this.
- Missing
- First impression was what views were the GD&T created did not seem to be the appropriate view for the best viewing.
- too simple. No assembly-level PMI, don't see all possible PMI types represented

- The information in some cases is a bit dense and overwhelming. Generally though it's ok. Color choice is good
- The GD+T looks OK. However, there does not appear to be potential for weld information.
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.
- A typical customer who uses PMI will have many more PMI's grouped (filtered) by Views.
- seems fine
- Why was the GD&T saved separately from geometry? Why not associated with views including geometry?
- adequate

Q20 (if Q19 = "I do not think the number…")

Why do you think the number of parts does not matter in having a benchmark model for testing?

- again, I would say that the issue is more about the complexity of the parts than the size (quantity). Also about relationships between parts.
- Once you get to 5 or 6 components - the rest is repeatitive. It is good to have an assembly of assemblies represented by the sissors.
- Because each product is different thus different amounts of parts are required to describe it for manufacture
- number of parts alone does not qualify for benchmark.
- the number of parts will only take in fact of Memory and hardware. will not matter in terms of content
- A large number of parts to produce in each of the systems from the ground up will be time consuming. The more parts, the more difficult it will be to find where errors arise. Testing large models is a different set of issues, that it sounds like this is trying to compare.

- Our machines have tens of thousands of parts. However, this would not be practical to work with. It is more important that the range of modeling features be covered than there be a large number of parts.
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.
- You can have a simple assemebly with just a few complex parts that will present complex positioning and surface machining requirements. Parts that have asthetic design requirements or deal with air of fluid flow of some kind are usually good candidates. Perhaps a stamped part, injection molded and multi axis machined part would be good.

Q22 (if Q21 = “the number of sub-assemblies does not matter”)
Why do you think the number of sub-assemblies does not matter in having a benchmark model for testing?

- Again it's not quantity but complexity of the product. Look at a complex composite for example. It's just a big inseperable assy, but the the explanation of how to add up the sum of the componenets is critical.
- Most CAD systems candeal with complex assembly structures
- assemblies are an outdated method of rating the complexity. complexity is defined by count but also number of variants and variant restrictions. Last but not least: "Structure doesn´t matter". The product structure is NOT defined by the creators, but by the consumers of teh product. there can be as many views on the product as there are consumers (downstream customers)
- As longer as there is one subassembly, that should be representative of others.
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.
- The number is less critical than ensuring all critical associations/relationships/conversions are properly addressed.

Q24 (if Q23 = Too little information present)

If there is too little information present, please explain:

- All of the conponents seem to be fairly simple to generate and put together? But there may be hidden complesity that can't be determined viewing the result. For example, modelling a corkscrew shape that follows a curve or spline and driven by parameters is more complex. And as I mentioned earlier - tapered fillets and shallow angle fillets are hard to see. But, it seems to be sufficient for this project?
- I could not look into the PRC file to determine the complexity of the data. Is it PRC or U3D, b-rep or visual data.

Q26 (if Q25 = Yes)

Why does the number of geometrically complex parts in a potential benchmark assembly model matter?

- my previous comments show that in order to "benchmark" a product definition and usage there are a lot more considerations.
- No - but having different complexity represented in different parts of the assembly is desireable. So, a sufficient number of complex parts is required.. Plus I can't determine if the benchmark assembly has a sufficient number of complex parts (question below) - because I can't determine the actual complexity of the components. For example the knife blades could have added a shallow angle fillet or tapered fillet?
- Shows the flexibilty and strength of the CAD Product
- So that you can have a benchmark that other products can be matched up with that are similar in complexity and the number of parts.
- number of features, kind of features used
- because some users don´t believe in simple assemblies.
- need to ensure that you have a good number of examples that are unique
- Scalability is a huge problem for many file formats. Weird things start to happen with massively large sets of data. And of course those are the harder ones to validate whether everything was converted properly.

- Calculations relating to construction and drawing of parts have a direct effect on the performance of a product, therefore it's benchmark as well. Although hidden from the end user, the complexity of the geometry under entities of parts will influence operations on these geometries be it conversion or simple rotation.
- Yes
- It seems to me that performance and file size differences should be part of the benchmark.
- The reason to model a part is so it can be manufactured, complex parts stretch the mfg solutions
- production models are complex and in places unclean

Q27 (if Q25 = No)

Why does the number of geometrically complex parts in a potential benchmark assembly model NOT matter?

- Make sure you have enough to adequately exercise all of the entity types in the STEP or JT standard.
- I think it can matter, but I think you have to work out the process and the results on the simpler set of cases first and then add other test cases as your process matures. Success or failure of exchange has lots of variables.
- As long as it is representative it should not matter.
- just need to ensure all use cases/types are comprehended.

Q30 (if Q29 = Yes)

Why does the number of parts in a potential benchmark model matter?

- How a CAD system utilizes Memory and Graphics is important once the users gets up to a larger assembly.
- Same as the other answer the benchmark should be similar in the number of parts and complexity as what you are benchmarking it against.
- -

- "Depends on what you are benchmarking? If it is just entity accuracy accross CAD tools....it probably doesn't. If you are exercising large complex assembly transfer, then it would matter."
- because users don´t believe in simple assemblies, with few numbers of parts
- It can, but again I think it is what you want ot test. If you want to test scalability then the number of parts matters. If you want to test geometry exchange and I told you 1 in 100 parts fails, does that mean you need at least 100 parts. I can easily build a test suite that has 100 parts and all translate fine. I can also bild an assembly with 100 parts that all have failures. What does it prove? The bottom line is if production data translates, which it does.
- Scalability is a huge problem for many file formats. Weird things start to happen with massively large sets of data. And of course those are the harder ones to validate whether everything was converted properly.
- Because the more parts you have the greater the need for processing speed. Scalability as well will be influenced greatly. Having many parts with simple geometries is never the same with having few parts with complex geometries.
- First you should have atomic or unit test parts that have each of the variations of an assembly. The scale the these to test for large assemblies. After this mix these cases into complex parts. I have worked with large assemblies the size of a large commercial passanger aircraft.
- Again to measure throughput

Q31 (if Q29 = No)

Why does the number of parts in a potential benchmark model NOT matter?

- just a complexity issue. what are you trying to accomplish with the "benchmark"?
- Because once you have 5 or 6 - the process is repeatative and unless you get to large enough number of parts to represent scalability testing.
- you can capture all geometric properties on a single model
- As long as the parts used are representative of industry parts, it should not matter.
- already answerd this

- See previous answers.
- Bechmarks should test assemblies in principle, thus a smaller number of parts is fine.

Q34

What could be improved and/or changed with the CAD model above?

- I found it hard to choose the previous answer. No matter what the product defintion is, PMI should tell the story of intent and usage. The types of products from structure, composites, systems (elec and mech) each have their own needs. The primary task is having enough intelligence to convey this. I am saying yes below with hesitations based on the above comments. I think that in order to study your subject of the survey, you will need to go into depth a lot further.
- The reason there should be more is that only a small sub-set of GD&T feature blocks were shown. But, this is not my area of expertise - so it is only an impression - not an opinion.
- Drive tooling and integrated product data Mgtmt.
- There may be things that need to be changed but I did not make the time to go into that much detail on my review of it.
- -
- Add lofted or sculpted surfaces, conics, threads, complex fillets/chamfers, axisymetric parts, complex features, repeating hole and feature patterns,
- -
- free form features to be included.... surface operations, sweeps, lofts, draft
- I think you have to start somewhere and the example is reasonable.
- Add more sub assemblies, more components, more PMI (including assembly-level PMI), and mix large components with tiny components (nuts and bolts), also should incorporate wiring, cabling, surface texturing, artwork (if possible)
- In the specific model I wouldn't change anything. For its size it has the necessary complexity.
- More PMI. Use some assembly level features (holes) and ideally harnesses.

- Look at the AIA LOTAR GD&T atomic test parts.
- For the specific example here, you may want to add embossed logos. Also, you may want to deal with issue of color priority. Typically, difference CAD systems have different color display priority: Part colort, face color, instance color..etc..How does translation deal with that?
- engrave something in the outside of the knife
- I want to see GD&T at the part ans assembly level.
- Add a bit more complexity to one model. The model should include all types of curves, surfaces (analytical and Nurbs) including free from surfaces and of course operations like fillets, offset surfaces, ..

Q36 (if Q35 = Yes)

Why do you think the model above could be a benchmark CAD model used throughout a company, organization, or industry for testing?

- It represents a minimum of complexity.
- Because it captures many of the complexities seen in a company. But, not all. To really evaluate the process would require a collection of models.
- If what is being benchmarked is similar in complexity and the number of parts,
- it is a good simple example for many use cases
- I think any parts that depeict a real set of parts is reasonable. If you expect that single set of parts to give you an interpolated view of what the success or failure in industry is based on this one assembly is unreasonable.
- As long as the range of features that could be used are included, it could be used as a benchmark.
- this part presents a die building excercise with some interesting assembly requirements. Very little machining, possibly a mold for the outer shape.
- Okay, I really don't know, but I couldn't really answer this question without seeing requirements/test cases.

Q37 (if Q35 = No)

Why do you think the model above could NOT be a benchmark CAD model used throughout a company, organization, or industry for testing?

- Products in todays industry are getting more complex everyday, users need a system that could grow with there needs. Simple assembly do not test out a system for this possible increased complexity
- I don´t think CAD models are needed for benchmarking / testing. CAD has come to an end, what really matters is PLM
- "Probably needs more complexity and features for an industy model. It may work for a company making simple products."
- It´s not a good idea on showing a knife to a company. The model is good, have a good number of parts. But a knife can cause a bad impression between you and the other person.
- too simple
- At least for the automotive sector where we are active the most, it is very small to be used as a proper benchmark. Usually the models are much more complex and big,
- You must have atomic test parts of EVERY type of data that needs to be translated.
- I believe one needs different benchmark model for different industry. Even within the same industry, say automotive, the typs of parts differ between powertrain and body-in-white. The former has many bulky parts while the latter is mostly surface models.

Q39 (if Q38 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could be made and used for an industry?

- basically, the CAD capability is there. Why not. just make sure to cover the intent and state the scope of the benchmark.

- Industries work on best practices. If one company in that industry is precieved to have an advantage, they will all adopt that best practice.
- To set up and control a corporate standard.
- In the auto industry you could make a model that represented the major types of geometry, PMI and manf process that one sees in a car.
- to show how the tool works, show all benefits you might have with an 3D viewing tool, and so on.
- that is a hard question
- I'll caveat that a single example gives you some insight. You cannot expect one set of parts and make industry conclusions.
- I'm not aware of any technical limitations that would prevent this, assuming the right authoring tool(s) are used to produce the model
- Because there are complex enough models to be used as a guide and they usually represent a real life case.
- Common needs suggest that a benchmark could be used
- Please check out LOTAR
- Generally, you may need more than model per industry.
- Sofware companies do this all the time, a representative part for an industry is created and then used when selling in that industry
- What else would you do?

Q40 (if Q38 = No)

Why do you think a potential benchmark model (not necessarily the model above) could NOT be made and used for an industry?

- Because there are only so many things you can put into any one model. This example certianly captures many of the necessary features. But, to really test the process will require a collection of part types. I don't think it is possible or desireable to put everything into a single model.
- PLM matters, not CAD

- the requiremnts within an industry are too heterogeneous and cannot be covered with only one benchmark model

Q42 (if Q41 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could be made and used for a company/organization?

[Area to freely write]

Q43 (if Q41 = Yes)

Why do you think a potential benchmark model (not necessarily the model above) could NOT be made and used for a company/organization?

- Proof of concept is in integral part of the design process. Validating the design and consumption of the product means cost savings.
- all depended on thier needs
- The same as my previous answer.
- Probably much easier. You can target company products and typical geometry for a benchmark example
- to show how the tool works, show all benefits you might have with an 3D viewing tool, and so on.
- it can be fine turned to handle all aspics of the company
- It can't hurt.
- again, I'm not aware of any technical limitations that would prevent this. The model would simply have to be a combination of models to be sufficient. I'm assuming the benchmark model is 100x more complex than anyone anywhere in the company/organization would face.
- Because for every type of company or organization there is a model that could represent a real life case.
- A company should have a defined set of standards that vendors would need to satisfy.
- Because this as a requirement for some industries.

- already answered this
- See previous answer.

Q45 (if Q44 = No)

Why do you think a potential benchmark model (not necessarily the model above) will NOT be different for every company/organization because of diverse requirements that each company/organization may have?

- Same answer - you need a collection of models to cover all the bases and still have designs that make sense. No one model will ever do that.
- -
- the requiremnts within an industry are too heterogeneous and cannot be covered with only one benchmark model

Q46

Any other thoughts or ideas about the CAD model shown above?

- If I was doing this I would choose something that reflects the products my company provides and validate that it represented what I needed to communicate. Communication is the key. Visualizing is one thing, consuming is another.
- Looks very good - I could see how some fillets and details (point on corkscrew) might add to complexity. Also, this part shape doesn't lend itself to evaluating complex surface issues like airfoils etc that might be desirable for some industries. That is why a collection of parts is required to really test out the interoperability issues with realistic parts.
- no
- Not really
- -
- Sounds like an interesting project. Talk with CAD vendors and their hotshot benchmarking folks. See what they do when they compete for business against other vendors and are asked to model parts from company X. CAD vendors

likely have some representative parts they use for testing software and competing for business.

- no.
- no
- This would be a very good example for a tutorial related to the hierarchy and general structure of CAD models since it is quite small. For industries it would be unusable. It would not offer usable benchmark results as it is very far off the usual specs of the automotive industry for example.
- No
- This is a very difficult because of the diversity of the customer requirements of each industry.
- Need to focus on accurate reprenstation of specific entities in a model, blends, complex surfaces, model size based on content (compression), abilty to make changes without corrupting the model. Benchmark parts always fall into catagories.
- nope

Appendix D. Participant Survey Contact Forms

Survey Contact Email

Subject Line: CAD Translation using a Benchmark Model – Survey for University Research

My name is Dillon McKenzie-Veal, and I am a graduate student working on my master's thesis entitled: "An Analysis of STEP, JT, and PDF Translation Between Constraint-based CAD systems with a Benchmark Model," under the direction of Nathan Hartman at Purdue University (NHARTMAN@PURDUE.EDU, 765-496-6104). My research is focused on analyzing the ability of STEP AP 203 edition 2, JT, and PDF to translate the necessary and correct information. Part of this research is using a benchmark model which was made to be comparable to an engineering CAD model that could be found in industry.

To accomplish this goal, I would appreciate if you or someone else you know who has knowledge and experience with CAD models could fill out a short online survey relative to this topic. Please forward this survey to anyone in your organization who has knowledge of CAD models. The survey will consist of questions designed to get your impressions of a CAD model and how it compares to CAD models you have interacted with in industry. A minimum of 10 years of experience working with computer aided design models is required to take the survey. This survey should take approximately 25-30 minutes, is voluntary, anonymous, and participants can stop at any time if necessary. No identifying information will be collected about you, or your organization. Participation or non-participation will not affect your job. All participants must be age 18 years of age or older.

All procedures and questions have been screened and approved by Purdue's Office of the Vice President for Research's Institutional Review Board for research involving human subjects.

Please click the following link which will take you to Purdue University's hosted survey site which has been constructed and administered by myself to collect information to identify specific strengths and weaknesses of a CAD model and how it compares to 3D CAD models you have interacted with in industry. The goal of this survey is to determine if the specific CAD model is a good representation of what could be found in industry and if not how it could be improved for a more accurate representation.

If you would like to participate please click on the following link:

[LINK TO INFORMATION SHEET]

Please complete the survey as soon as possible.

Feel free to contact me at 765.496.6104 or DMCKENZ@PURDUE.EDU if you have questions or concerns regarding this online survey. If you have concerns about the treatment of research participants, you can contact the Institutional Review Board at Purdue University, Ernest C. Young Hall, Room 1032, 155 S. Grant St., West Lafayette, IN 47907-2114. The phone number for the Board is (765) 494-5942. The email address is irb@purdue.edu.

Thank you for your time!

Dillon McKenzie-Veal
Graduate & Research Assistant
Computer Graphics Technology, Knoy Hall
Purdue University, West Lafayette, IN
DMCKENZ@PURDUE.EDU
765.496.6104 (voice)

Nathan W. Hartman, Ed.D.
Department of Computer Graphics Technology
NHARTMAN@PURDUE.EDU
765.496.6104 (voice)

Survey Reminder Email, to be emailed one week after initial email

Subject Line: CAD Translation using a Benchmark Model – Survey for University Research, Reminder

Approximately a week ago, you received an email request to participate in a Purdue University study about the use of a benchmark model in CAD file translation and how the benchmark model compares to model found in industry. If you already completed the survey, thank you very much! Your participation is greatly appreciated. If you have not already participated, please do so at your earliest convenience.

The survey will consist of questions designed to get your impressions of a CAD model and how it compares to CAD models you have interacted with in industry. A minimum of 10 years of experience working with computer aided design models is required to take the survey. This survey should take approximately 25-30 minutes, is voluntary, anonymous, and participants can stop at any time if necessary. No identifying information will be collected about you, or your organization. Participation or non-participation will not affect your job. All participants must be age 18 years of age or older.

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Thank you for your time!

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