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DIGITIZING AMERICAN MANUFACTURING

DMDII FINAL PROJECT REPORT

Supply Chain TDP Improvement Through DMDII	
Project Team Lead	Rolls-Royce Corporation
Project Designation	14-06-01 – Supply Chain TDP Improvement Through DMDII
UI LABS Contract Number	02201600002
Project Participants	Lockheed Martin Corporation, ITI, Purdue University (&3rd Dimension), Anark Corporation, Zeiss, Siemens and Microsoft
DMDII Funding Value	$1,420,292
Project Team Cost Share	$1,587,356
Award Date	14 January 2016
Completion Date	14 July 2017

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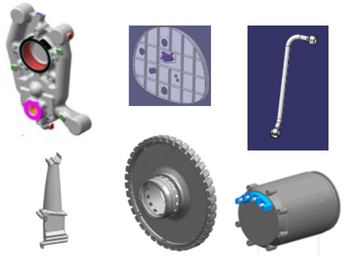
I. EXECUTIVE SUMMARY

Traditionally 2D drawings have been used for communication of design, manufacturing and inspection requirements through the supply chain and product lifecycle. However those drawings are typically supplemented with a 3D Model of the geometry. That model in some cases is used as a main source for geometric elements. This leaves supply chain with possibility of conflicting data between 2D and 3D, which in turn creates a lack of data integrity, rework, confusion and loss of time/productivity. With the advent of Model Based Definition (MBD) and Enterprise (MBE), those barriers to communication have been reduced, if not removed altogether. However, the adoption of MBD/MBE methodologies and software usage has been impeded by the availability of software and standards throughout the supply chain, as well as the maturity of the MBD technology. The project evaluated where current technology stands to support how the supply chain operates in a MBE system. MBD data needs to be available to the supply chain in a usable, accurate and standard format. The process of delivering the MBD is best managed as a Technical Data Package (TDP) with multiple neutral formats, suitable for supplier's capabilities for consumption. Along with the limited availability of software is limited training and knowledge of how to create and utilize the MBD data.

The project reviewed software capability to create, translate, validate and provide MBD data for a supply chain to consume. The project did not fully evaluate accuracy of MBD data being translated to the various neutral formats used on the project. Only that MBD data, via a TDP, could be transferred and consumed by supply chain. This was accomplished by selecting several design test cases and generating MBD data to be processed through a complete supply chain, from top-level OEM (Lockheed Martin), mid-level OEM (Rolls-Royce), and vendor level (Zeiss, Purdue/3rd Dimension). The MBD data, which consisted of geometry, Product Manufacturing Information (PMI), attributes and supplemental documentation, was created, using various CAD systems (Siemens NX, Dassault Catia) and other software. The design information did not include 2D drawings. The project completely relied on MBD to communicate all design, manufacturing and inspection data. The 3D data was translated and validated to various neutral formats (STEP, JT, 3D PDF) using ITI and Anark software. The packages of design data were assembled into TDP packages and sent to the supply chain (Figure 1). The TDP/MBD was consumed by the supply chain as needed to complete a simulated real-world design/manufacturing/inspection task. A design change was introduced into the process. From the "round-trips" through the supply chain, lessons were learned, documented; training and guidelines were developed to better educate OEM and supply chain on the current state of MBD/MBE/TDP capabilities. All of which are just a snap-shot of current capabilities by the software companies used on the project. Advancements and support of standards by organizations, providers, consumers, and industry continue to improve and learn.



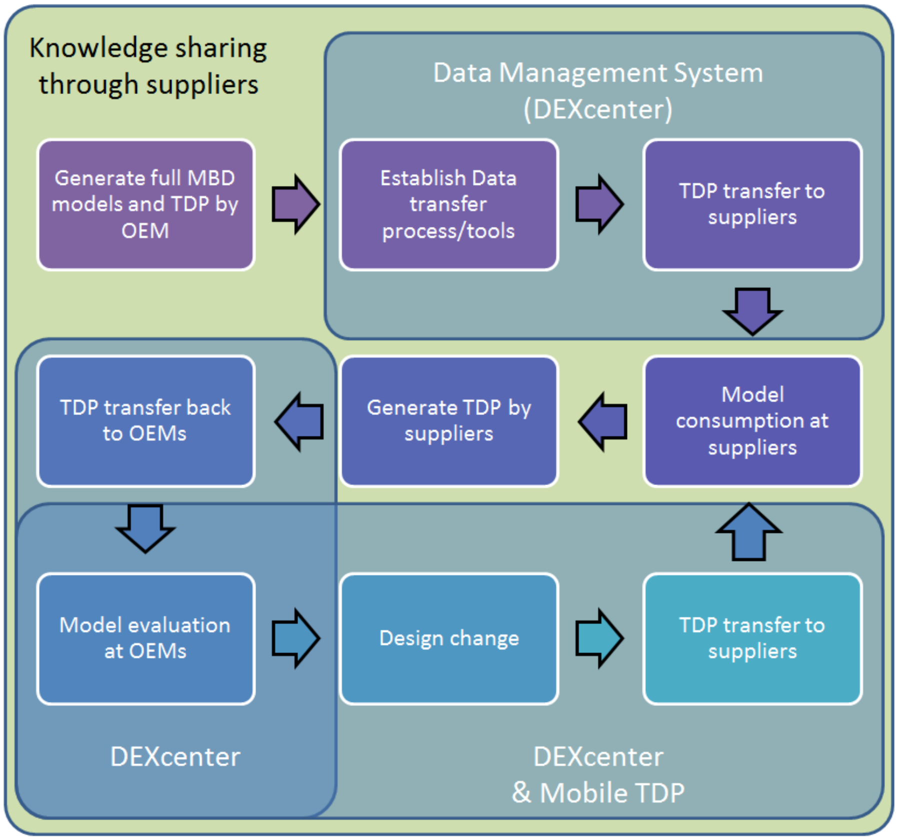


Figure 1: TDP/MBD Project Flow

The project was able to demonstrate the usage of the MBD neutral formats being consumed through the supply chain. As will be highlighted, emerging technology to support semantic (i.e. geometrically associative) representation of the MBD data became available just at the onset of the project. Emerging technology availability to supply chain proves the difficulty for complete adoption of MBD through the entire supply chain. Given varying CAD systems within the supply chain and OEMs, the importance of a CAD neutral format becomes evident quickly. Not only is building proper design intent into the MBD important based on requirements established by company and industry, but also the consistency between the original CAD and neutral formats, as to not lose the intent and data integrity. Results for the currently available formats were documented (See Appendix A). The compliance with industry standards (e.g. STEP AP242, ASME Y14.41) and/or company standards during creation, translation, and validation is vastly important for OEMs to be able to communicate full design intent throughout the supply chain. OEMs and suppliers are encouraged to use the latest software to gain the most benefit from working in a Model Based Enterprise. The guidance and lessons learned from this project will assist with the understanding of where technology is currently. Additionally, it is recommended to implement a standard approach to the deployment and use of MBD within supply chain by setting company standards and methods for creation, translation, validation and sharing data.

II. PROJECT REVIEW

The primary objective of this program is to evaluate the current and emerging Model-Based Enterprise (MBE) technologies used to achieve step changes in utilizing advanced product definition methodology well beyond just part geometry with associated attributes in the Technical Data Package (TDP) through the supply chain.

Model-Based Enterprise (MBE) is a critical technology that is changing how design and manufacturing information is shared, such as design models/criteria, manufacturing process models/information, supply chain (internal & external) communications, and enterprise-wide information. The outcome of the project is intended to resolve the current 'silo' environment among internal functional groups and through the supply chain and accelerate progress on digital communication between design and manufacturing. This project enabled support of fully annotated 3D models based on the latest MBD and TDP standards; demonstrating secure, digital transfer of these 3D models to and from suppliers, and provided the MBE requirements demonstrating supply chain integration.

The major objectives are:

1. Improve knowledge/data sharing and enhance product quality through the supply chain
2. Accelerate the maturation of full Model-Based Definition (MBD) methodology via STEP AP242, JT and 3-D PDF
3. Accelerate the maturation of the DMDII Digital Manufacturing Commons (DMC) infrastructure
4. Improve MBD TDP training curriculum in academia and in industry
5. Develop connectivity within the NNMI structure through collaboration with America Makes to apply MBD for additive manufacturing processes.

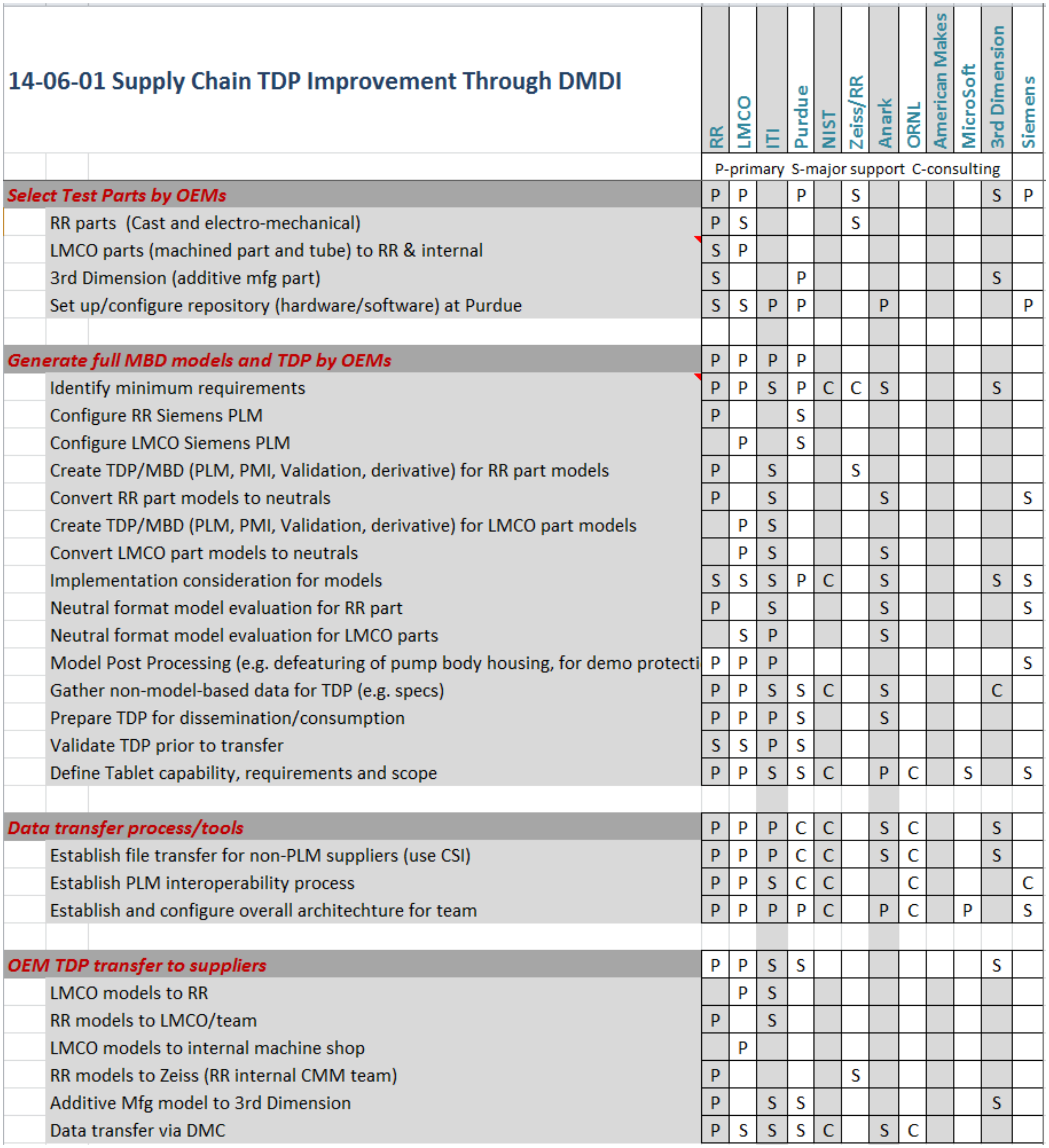
MBE can offer significant long term time and cost savings by enabling enriched product definitions, enterprise wide information integration, and data re-use through supply chain and the entire product lifecycle. It can also facilitate a systematic framework for knowledge sharing through the internal and external supply chain. On the production definition front, the resulting technology can accelerate progress on totally eliminating drawings and provide ability to operate on intelligent 3D product models.

In addition to optimizing communication between design and manufacturing, this project also established partnering opportunities with key suppliers. Rolls-Royce as an Engine OEM brings relevant TDP program experience and created and received TDP/MBD for this technology demonstration, in addition to overall project coordination. Lockheed Martin (LMCO) is an Airframe OEM and brings Customer/Supplier Interoperability (CSI) and MBD program expertise to the team. LMCO also created TDP/MBD data to provide to the team. Purdue University brings a depth of MBE and MBD experience to the team and represented the interests of academia. Purdue was the key contributor to developing and defining the appropriate curriculum for training existing and future design and manufacturing engineers.

Purdue subcontracted 3rd Dimension, a small Indiana business, for the additive manufacturing of a test part. Anark is a major MBE visualization vendor with HTML5 and PDF products and participated in the mobile based knowledge sharing demonstration tasks. ITI Transcendata led the translation/validation of Product and Manufacturing Information (PMI; i.e. 3D annotation/dimensions) models in neutral formats related tasks and they bring expertise in the area of interoperability. ITI was responsible for tasks related to knowledge sharing and change management. Microsoft provided in-kind cost share in the form of software licenses to enhance team communication and provided the tablets for the shop floor visualization demonstration. Zeiss Corporation functioned as the primary consumer of the MBD/TDP data, demonstrating the consumption of MBD CAD data, utilizing the MBD data to perform inspection tasks.

The Work Breakdown Structure (WBS) is shown in Figure 2 along with the designation of each partners anticipated contribution during project execution. The letters within the intersecting cells indicate the level of participation anticipated for each of the partners for a particular task. A “P” indicates a primary role, and “S” indicates a major supporting role and a “C” indicates a consulting role for the individual tasks.

Rolls-Royce, as well as the partner companies, demonstrated the benefit from the standardization of communication tools within the industry to create a more efficient process for designing and manufacturing products. By jointly developing methods and environments to share knowledge for design and manufacturing, shorter lead times and ultimately reduced product costs are anticipated. Developing best practice use of fully annotated 3D MBD across the supply chain enables efficient and timely transfer of data. This was demonstrated within a controlled process to ensure compliance to rules and regulations. Providing real-world, practice-based MBD guidelines for training the incumbent and future workforce will ultimately improve U.S. industry competitiveness.

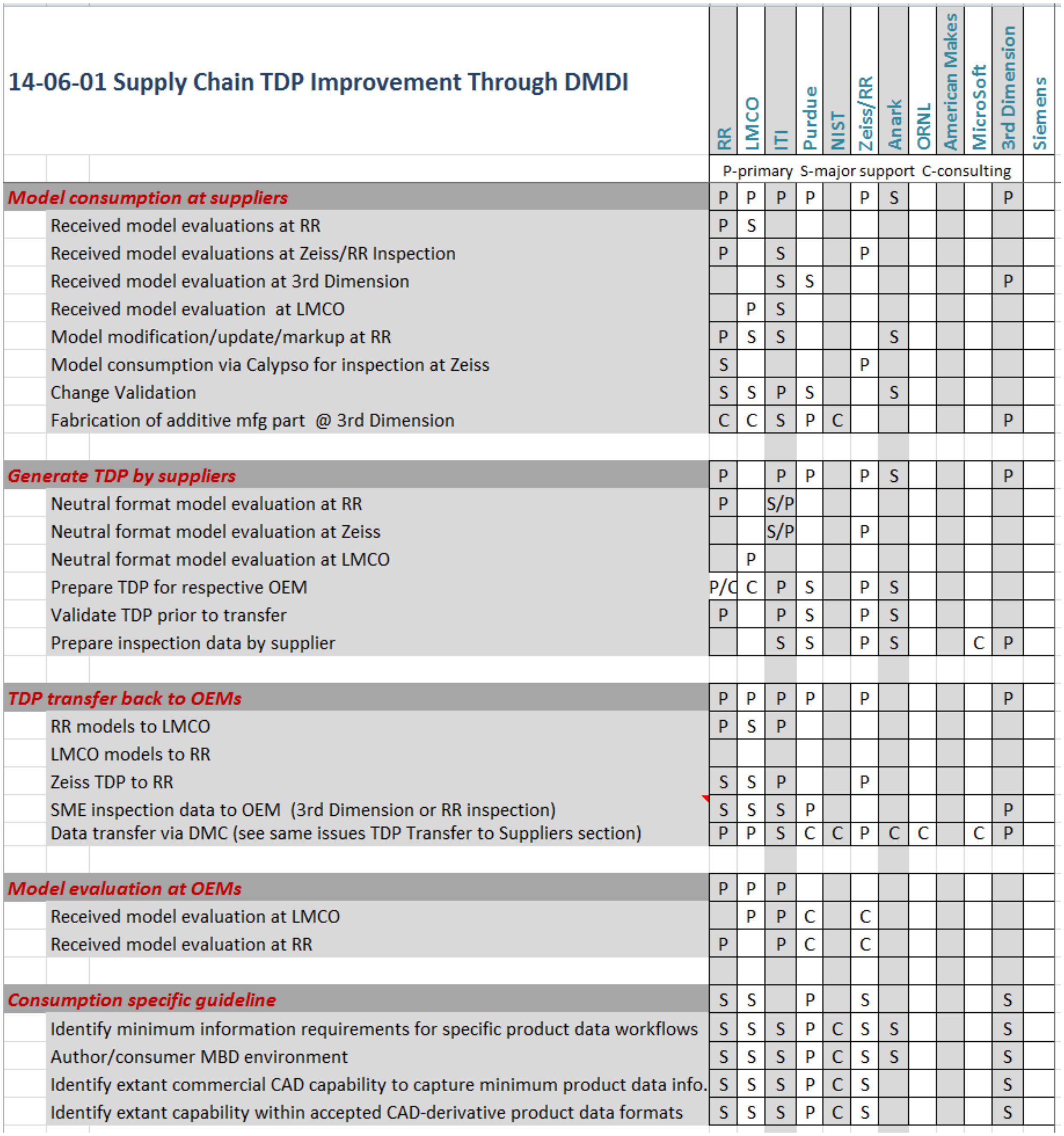


14-06-01 Supply Chain TDP Improvement Through DMDI

P-primary S-major support C-consulting

14-06-01 Supply Chain TDP Improvement Through DMDI	RR	LMCO	ITI	Purdue	NIST	Zeiss/RR	Anark	ORNL	American Makes	MicroSoft	3rd Dimension	Siemens
Select Test Parts by OEMs	P	P		P		S					S	P
RR parts (Cast and electro-mechanical)	P	S				S						
LMCO parts (machined part and tube) to RR & internal	S	P										
3rd Dimension (additive mfg part)	S			P							S	
Set up/configure repository (hardware/software) at Purdue	S	S	P	P			P					P
Generate full MBD models and TDP by OEMs	P	P	P	P								
Identify minimum requirements	P	P	S	P	C	C	S				S	
Configure RR Siemens PLM	P			S								
Configure LMCO Siemens PLM		P		S								
Create TDP/MBD (PLM, PMI, Validation, derivative) for RR part models	P		S			S						
Convert RR part models to neutrals	P		S				S					S
Create TDP/MBD (PLM, PMI, Validation, derivative) for LMCO part models		P	S									
Convert LMCO part models to neutrals		P	S				S					
Implementation consideration for models	S	S	S	P	C		S				S	S
Neutral format model evaluation for RR part	P		S				S					S
Neutral format model evaluation for LMCO parts		S	P				S					
Model Post Processing (e.g. defeaturing of pump body housing, for demo protecti	P	P	P									S
Gather non-model-based data for TDP (e.g. specs)	P	P	S	S	C		S				C	
Prepare TDP for dissemination/consumption	P	P	P	S			S					
Validate TDP prior to transfer	S	S	P	S								
Define Tablet capability, requirements and scope	P	P	S	S	C		P	C		S		S
Data transfer process/tools	P	P	P	C	C		S	C			S	
Establish file transfer for non-PLM suppliers (use CSI)	P	P	P	C	C		S	C			S	
Establish PLM interoperability process	P	P	S	C	C			C				C
Establish and configure overall architechture for team	P	P	P	P	C		P	C		P		S
OEM TDP transfer to suppliers	P	P	S	S							S	
LMCO models to RR		P	S									
RR models to LMCO/team	P		S									
LMCO models to internal machine shop		P										
RR models to Zeiss (RR internal CMM team)	P					S						
Additive Mfg model to 3rd Dimension	P		S	S							S	
Data transfer via DMC	P	S	S	S	C		S	C				

Figure 2: Project WBS

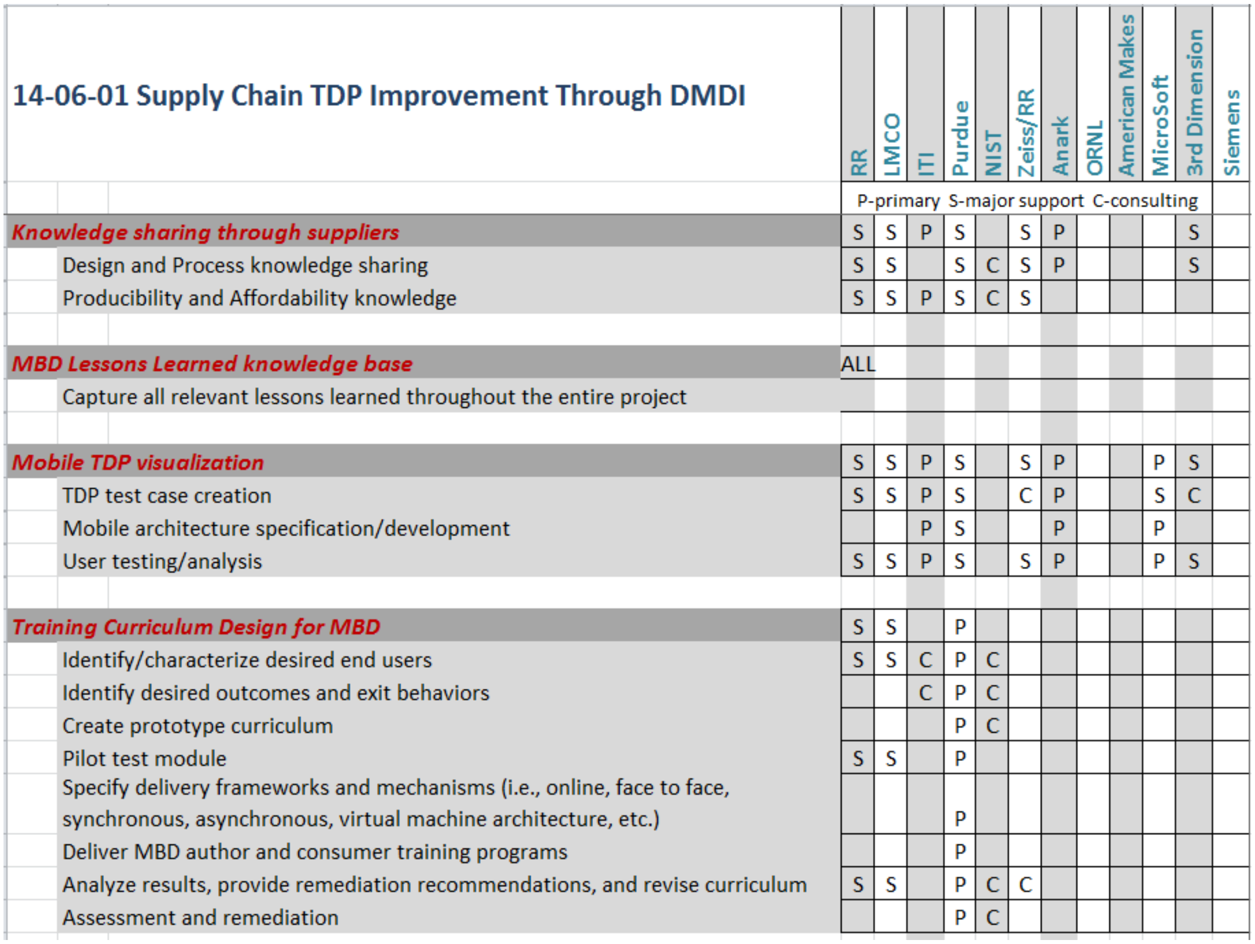


14-06-01 Supply Chain TDP Improvement Through DMDI

P-primary S-major support C-consulting

	RR	LMCO	ITI	Purdue	NIST	Zeiss/RR	Anark	ORNL	American Makes	MicroSoft	3rd Dimension	Siemens
Model consumption at suppliers	P	P	P	P		P	S				P	
Received model evaluations at RR	P	S										
Received model evaluations at Zeiss/RR Inspection	P		S			P						
Received model evaluation at 3rd Dimension			S	S							P	
Received model evaluation at LMCO		P	S									
Model modification/update/markup at RR	P	S	S				S					
Model consumption via Calypso for inspection at Zeiss	S					P						
Change Validation	S	S	P	S			S					
Fabrication of additive mfg part @ 3rd Dimension	C	C	S	P	C						P	
Generate TDP by suppliers	P		P	P		P	S				P	
Neutral format model evaluation at RR	P		S/P									
Neutral format model evaluation at Zeiss			S/P			P						
Neutral format model evaluation at LMCO		P										
Prepare TDP for respective OEM	P/C	C	P	S		P	S					
Validate TDP prior to transfer	P		P	S		P	S					
Prepare inspection data by supplier			S	S		P	S			C	P	
TDP transfer back to OEMs	P	P	P	P		P					P	
RR models to LMCO	P	S	P									
LMCO models to RR												
Zeiss TDP to RR	S	S	P			P						
SME inspection data to OEM (3rd Dimension or RR inspection)	S	S	S	P							P	
Data transfer via DMC (see same issues TDP Transfer to Suppliers section)	P	P	S	C	C	P	C	C		C	P	
Model evaluation at OEMs	P	P	P									
Received model evaluation at LMCO		P	P	C		C						
Received model evaluation at RR	P		P	C		C						
Consumption specific guideline	S	S		P		S					S	
Identify minimum information requirements for specific product data workflows	S	S	S	P	C	S	S				S	
Author/consumer MBD environment	S	S	S	P	C	S	S				S	
Identify extant commercial CAD capability to capture minimum product data info.	S	S	S	P	C	S					S	
Identify extant capability within accepted CAD-derivative product data formats	S	S	S	P	C	S					S	

Figure 2 (continued): Project WBS



14-06-01 Supply Chain TDP Improvement Through DMDI	RR	LMCO	ITI	Purdue	NIST	Zeiss/RR	Anark	ORNL	American Makes	MicroSoft	3rd Dimension	Siemens
	P-primary S-major support C-consulting											
Knowledge sharing through suppliers	S	S	P	S		S	P				S	
Design and Process knowledge sharing	S	S		S	C	S	P				S	
Producibility and Affordability knowledge	S	S	P	S	C	S						
MBD Lessons Learned knowledge base	ALL											
Capture all relevant lessons learned throughout the entire project												
Mobile TDP visualization	S	S	P	S		S	P			P	S	
TDP test case creation	S	S	P	S		C	P			S	C	
Mobile architecture specification/development			P	S			P			P		
User testing/analysis	S	S	P	S		S	P			P	S	
Training Curriculum Design for MBD	S	S		P								
Identify/characterize desired end users	S	S	C	P	C							
Identify desired outcomes and exit behaviors			C	P	C							
Create prototype curriculum				P	C							
Pilot test module	S	S		P								
Specify delivery frameworks and mechanisms (i.e., online, face to face, synchronous, asynchronous, virtual machine architecture, etc.)				P								
Deliver MBD author and consumer training programs				P								
Analyze results, provide remediation recommendations, and revise curriculum	S	S		P	C	C						
Assessment and remediation				P	C							

Figure 2 (continued): Project WBS

III. KPI'S & METRICS

Several performance metrics were identified at the onset of the project. The metrics were aimed at ways of improving communication of engineering data through the supply chain, using the latest MBD/TDP tools and processes offered by a select few software vendors. The "As-is" method was traditional 2D drawing based processes that used little or no 3D model data in the communication of engineering definition. The goals were set to purely rely on current 3D MBD/MBE technology, including several 3D derivatives (PDF, STEP, JT), and the latest additive manufacturing capabilities (3MF).

Table 1: Project Metrics

Metric	"As-is" baseline	Project goal	Results	Validation Method
Ability to utilize MBD neutral format for TDP transfer through supply chain	Mainly drawing base with supplementary 3-D models and manually collected individual electronic files.	Semi-automated generation of TDP with change management and traceability.	TDP packages in the format of zip or PDF containing 3D PDF, JT and STEP were generated thru DEXcenter Workflows. DEXcenter tracks the TDP and retains for a specified period	Testing
Ability to use STEP AP242 as a common standard for MBD transfer.	Not using PMI schema in MBD models, AP242 yet to be released. Use traditional human interpretation of product definitions	Ability to utilize AP242 with PMI based annotation.	See Model Consumption (section E) and Results (Appendix A). Siemens supports in NX11 as of Aug 2016. Fair results. Dassault limited support in Catia V5R2016. Plan Catia release late 2017. Limited testing in Solidworks 2017. No other CAD systems tested	Testing and research
Ability to use JT and 3-D PDF as an alternative derivative format for model transfer	Utilized in the traditional modeling context. Almost none include PMI annotation	Evaluation of the JT and PDF capability to handle PMI based full MBD	See Model Consumption (section E) and Results (Appendix A). Evaluated Siemens JT11 and Anark 3D PDF abilities properly translate semantic PMI	Testing and comparison using CADIQ
Interoperability on TDP exchange among different system environment	Multiple neutral and proprietary formats that do not maintain fidelity with each other. Billions of dollars lost and much non-value added activity	A prototype installation of a neutral exchange mechanism amongst disparate model-based formats and their respective derivative formats	DEXcenter was set up at Purdue to translate data to neutral derivatives (STEP, JT, 3D PDF)	Usage during project
Ability to systematically share engineering and processing knowledge across supply chain	Ad-hoc and personal based via meetings, email exchanges, etc. Lack of engineering communication between suppliers and OEMs	Establish a preliminary framework and platform to enable systematic communication among engineering in the supply chain.	Properly formatted TDP in form of PDF, containing all native, derivative and supplemental data. Demonstrated with PDF template used on project data and shared amongst team.	Testing and usage during project

Metric	"As-is" baseline	Project goal	Results	Validation Method
Ability to utilize mobile devices for interactive TDP communications	On regular PCs with files and model display. No associativity between model and document data	Tablet based TDP with substantial linkage between 3-D geometry/ annotations with document data and facilitating interactive commenting.	Demonstrated use of PDF-based TDP (also limited HTML use) on multiple devices (laptop, tablet and mobile). Including retaining semantic associativity between PMI and geometry.	Testing and usage during project
Establish minimum information necessary to make MBD communication successful within specified workflows	Exists usually as either minimal annotations on the 3-D model or every feature is dimensioned/annotated/controlled	Identify information requirements by model consumers in specific workflows. Authors are advised and trained via the new curriculum for constructing MBD accordingly.	Tutorial created that includes the minimum information for TDP and MBD.	Reviewed by persons uninvolved with project and unfamiliar with MBD/TDP
Establish a prototype process for SMEs with additive manufacturing capability to consume model-based TDPs for production and inspection	Primarily revolves around using drawings at most SMEs, although SMEs with additive manufacturing capability must use 3-D models by default	Develop a matrix that identifies MBD-friendly techniques and command functionality within contemporary CAD tools	Determined that additive manufacturing processes are not able to consume semantic PMI MBD data at the time of this project. Able to read MBD data via PDF format and use 3D CAD-related data (STL file) via existing methods.	Testing with additive manufacturing SME and America Makes representative
Enhanced curriculum to include model-based TDP content	Training practice is specific to software brands and small classes, as well as specific corporate practice	Able to combine software use with corporate practice. Lessons learned from multiple OEMs with a mixture of procedural and declarative knowledge. Focus on practical MBD applications.	Tutorial created that focused on MBD/TDP generation. Software was identified that provides the functionality to support MBD consumption through supply chain. Tutorial also includes lessons from OEMs.	Testing and usage during project
Ability to use DMC for TDP transfer through the supply chain	Existing internet is not a secure network and it does not have an open source environment for manufacturing supply chain	Depending on the development result of DMC technology, this program will implement the DMC network wherever applicable for TDP transfer. This program will offer	DMC was evaluated multiple times during project. During period of project it was determined that DMC was not secure enough for sharing IP related data. Further testing of DMC was not pursued. Feedback was provided separately to DMC team.	Testing and usage during project

Metric	“As-is” baseline	Project goal	Results	Validation Method
		lessons learned feedback to the DMC team.		

IV. TECHNICAL DEVELOPMENT/ ASSESSING THE TECHNOLOGY

The technical activities of the project involved the selection of parts, creation and validation of MBD/TDP data (NX and Catia, PDF, STEP, JT, supplemental documents) by OEM, transfer and consumption of data by supply chain, creation of supplier MBD/TDP as needed and transfer back to OEM. The activities align with the WBS in Figure 2. The project was concerned with real-life flow of data, not isolated test cases. Focus was put on success of MBD data creation, translation, validation and consumption to convey complete and accurate definition through supply chain.

This project reviewed the capabilities offered by a limited number of companies, as a snap shot in time with the understanding that there are still development activities, which may not completely represent their latest capabilities. The software used was setup at Purdue University as a neutral location, as well as functioning as part of the supply chain.

A. Select Test Parts by OEMs

Test parts were chosen from two separate OEMs, Rolls-Royce and Lockheed Martin, based on their varied complexity. The Rolls-Royce Oil Pump Body Housing (Figure 3) was the main focus for a majority of the technical activity. The part was basic prismatic geometry that had multiple types of casting features.

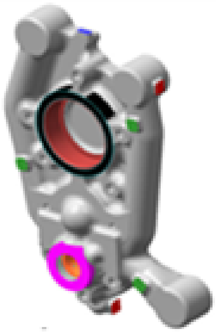


Figure 3: Rolls-Royce Oil Pump Body Housing Model

Lockheed Martin (LM) identified a part that was realistic and applicable for an aircraft OEM that could be beneficial for the teams involved. The decision was made to use a structural bulkhead component typical of most aircraft design and manufacturing capabilities, Figure 4. The premise of using a generic bulkhead was to use the features and contour characteristics of a slightly complex component. Additionally, to support design in context, integration and assembly with the Rolls-Royce oil pump body housing to the bulkhead, LM opted to generate a tube (Figure 8) with various bends which could be attached to the oil pump body housing. An additional report, provided in attachments, covers the Lockheed Martin's internal tube process and their review of their tube process use of TDP/MBD for model based manufacturing.

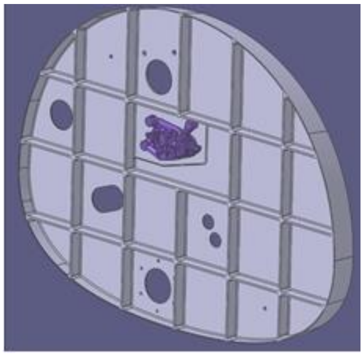


Figure 4: Lockheed Martin Bulkhead Model

Additional data (Figures 5-8) was selected to perform complete testing on the software tools being evaluated for definition to be shared with supply chain.

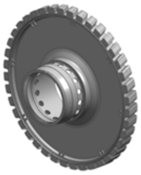


Figure 5: RR Disk

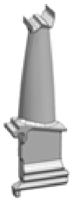


Figure 6: RR Blade

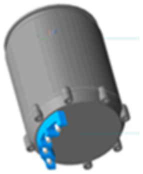


Figure 7: RR Generator

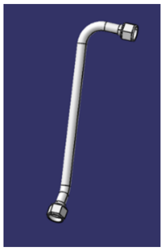


Figure 8: LM Tube

In an effort to use data that represented common requirements in industry, a set of minimum requirements were established. The requirements in Table 2 were based on those provided in ASME Y14.41 (Digital Product Definition Processes). The requirements were chosen to focus on a known set of industry-based standards and to limit the types and amount of data during the project. The MBD generated for the project was part of the TDP requirements in Table 3 which was provided to supply chain. The TDP requirements were chosen to focus the project on a subset of the numerous requirements and data types that could be in a TDP. The TDP creates a complete definition package for suppliers, with the added benefit of access to the 3D content for consumption directly into software.

Table 2: MBD Minimum Requirements

MBD data (created in NX and Catia) (reference ASME Y14.41)	
3D Model	
	geometry (e.g. solids/surfaces)
	supplemental geometry (e.g. curves, datum planes)
	others : non-modeled geometry (e.g. threads)
	non-assembly data
PMI/Annotation	
	based on ASME Y14.5 (GD&T)
	semantic/associated to appropriate geometry (faces, edges, points, etc.)
	others: symbols for company-specific manufacturing process for associating to features to provide direction. Decided to stay with industry-based symbols
	use design tools to ensure proper definition complies with standards
	use of guidance material to designers for metrology support, to allow for ease of inspection
	other non GD&T annotation with no standard. Use some to test capability of translation, consumption
attributes/metadata (embedded within CAD data or separate document	
	material, management data, revision control
	accompanying documents that has title block, revision control, notes, etc. in a separate document

Table 3: TDP Requirements

TDP Requirements (reference Mil-Std-31000A)	
MBD data (as defined in Table 2)	
BOM (as applicable)	
Specification/Standards	
	Engineering
	Industry
Neutral/Derivative data	
	3D PDF
	JT
	STEP (203/242)

Reports/documents	
	Inspection (e.g. First Article Inspection)
	Checking

Several use cases were considered to cover as many real-life scenarios as possible. The cases tried to account for various definition consumption areas (design, manufacturing, inspection, etc.) and the data formats that would be needed to properly consume data. Table 4 shows all of the cases and corresponding data formats that were considered and those that were finally agreed (as marked by ‘X’). The cases selected were chosen based on those that could be accomplished within the timeframe of the project. There were two formats (STEP AP242 and JT) that were attempted for inspection, but the ability to use those formats ended up unsuccessful.

Table 4: Project Use Cases

In Scope	**Use Cases for MBD and TDP communication**			**Data Formats** (“x” indicates Use Case/format used; “-“ indicates Use Case/format attempted)											
				CAD	**PDF**	**STEPAP203**	**STEPAP242**	**JT**	**STL/3MF**	**Word**	**BCT Data**	**GCODE**	**DMIS**	**QIF**	**TDP Template**
x	Design			x	x	x	x	x							x
x	Change Management			x	x		x	x		x					x
		Documentation			x					x					
		Partner Exchange of CAD data		x	x		x	x		x					
	Manufacture														
		Traditional (simulated)													
x		Additive (actually performed)			x				x						x
x	Inspection			x			-	-					x		x
x		First Article Inspection Report process			x			x			x				x
	Intellectual Property														
	LOTAR														
x	Non-geometric (specs, material, process)				x					x					x
		Test Procedures													
	Systems Engineering requirements														
	Cost model data														

x	Assembly			x				x							x
x		EBOM													x
		MBOM													
		ABOM (asy module assembly)													
		Process planning													
		Asy PMI													
		Work Instructions													
		Services													
		Kitting													

B. Generate full MBD models and TDP by OEMs

Each of the 3D CAD models, from NX and Catia, had PMI applied, per Table 2, to provide definition intent and requirements to be consumed downstream by manufacturing and inspection. The PMI was required to be semantically (i.e. geometrically associated) applied to the model. The MBD data (CAD model with PMI) was translated to STEP AP203 and STEP AP242 using internal CAD translators and third-party software (ITI CADIQ, Theorem Solutions). AP203 is an established neutral solid model format that exchanges solid model and non-associative PMI. AP242 is a newly available neutral solid model format that contains associative PMI. The MBD data was also translated to JT and 3D PDF using internal CAD translators and third-party software (ITI CADIQ, Anark, Theorem Solutions). Both of JT and 3D PDF formats have been available in the marketplace for many years. These formats provide a non-CAD-based visualization method for downstream users. Along with the 3D MBD files, ancillary data, typically documents (e.g. Specification/Standards, First Article Inspection Reports, and Notes) was provided as part of the TDP. The TDP also consisted of supplier-specific data, dependent on data usage. For example, additive manufacturing uses STL or 3MF files more than STEP or JT.

Rolls-Royce used Siemens NX version 9 and 11 to create the MBD model data (Figure 9). NX9 was chosen because NX11 was not released until August 2016, several months after beginning project technical activity. NX11 was leveraged into the project activities primarily for the availability of STEP AP242. As well as improved capabilities with PMI. Given NX11 being newly released during the project, the two NX (version 9 and 11) models were maintained to be able to test with the various software and suppliers used on the project, as they were not able to directly consume NX11 data. Rolls-Royce includes the attribute/metadata (e.g. material information) as part of the CAD model in the form of PMI. In addition to the NX data, an Excel spreadsheet for First Article Inspection data was created using BCT Inspector software. The NX and Excel data was processed through Anark software to create the 3D PDF. NX11 was also capable of directly printing to a 3D printer that supports 3MF format, but could not directly output/export a 3MF file that would then be consumed. Siemens Teamcenter Visualization is capable of converting JT data to 3MF file, which was provided as part of the TDP.

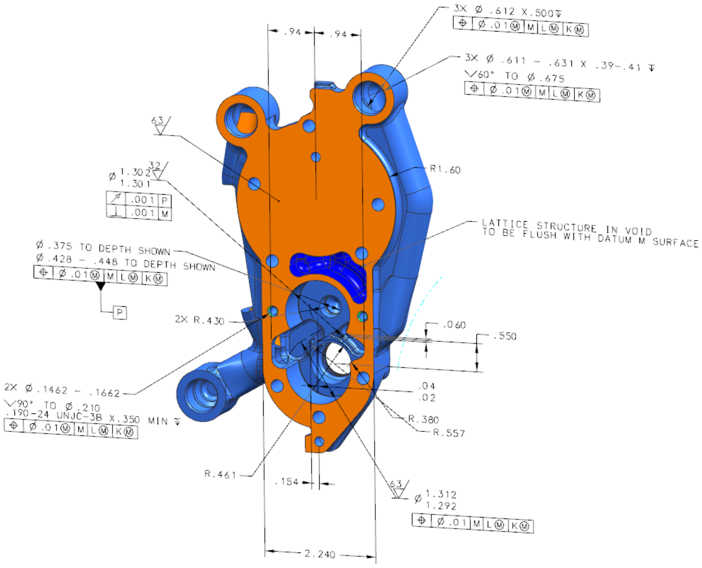


Figure 9: RR Oil Pump Body Housing MBD

Lockheed Martin used Dassault Systemes CATIA V5 software as the primary CAD system to develop the 3D Product definition models. The models for the bulkhead (Figure 10) and tube parts were created using both CATIA V5 R24 and R26 to enable project translation capabilities. Once the geometrical models were created and manipulated to represent a realistic assembly design of a structural component with attached system integration, then both the detail components and the assembly were annotated with product manufacturing information (PMI). The bulkhead and tube component each have detail level semantic PMI that enables the part to be fabricated, inspected and installed plus there is assembly level PMI. The PMI was created using the CATIA V5 Functional Tolerance & Analysis (FT&A) workbench providing tools that enable accurate and appropriate semantic Geometric Dimension & Tolerance annotations to the ASME Y14.5 standard. Additionally, the model was set up in the configuration of ASME Y 14.41 standard. A Technical Data Package (TDP) was created which contained the following data CATIA V5 R24 & R26, STEP AP203 & AP242 translation, JT model, First Article Inspection (FAI) document, two Transmittal Documents (one in typical Lockheed Martin format and one in Purdue format) and notes.

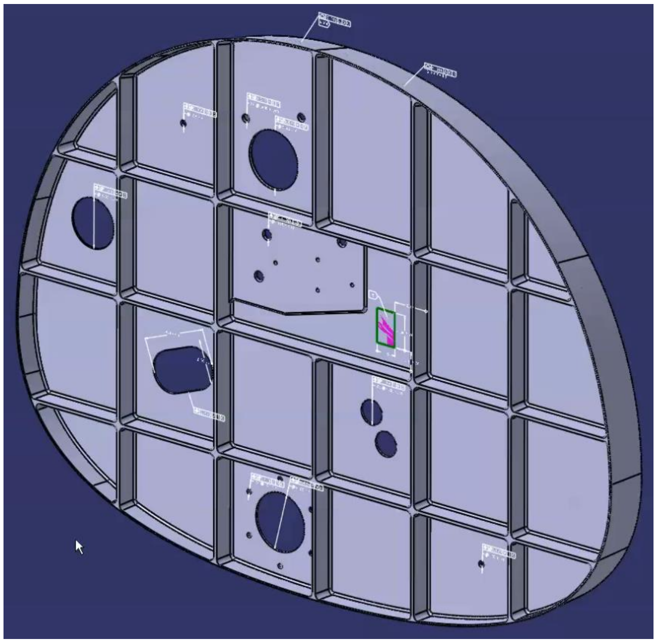


Figure 10: LM Bulkhead MBD

Anark Core Workstation (ACW) was used to publish 3D PDF TDP (Technical Data Packages) from CATIA and NX models provided by Lockheed Martin and Rolls-Royce, respectively. In addition to product geometry, assembly structure, 3D dimensions and tolerances, and product metadata available within the CAD files, a bill of characteristics was also imported and published into the 3D PDF artifacts by the ACW software. Anark contributed skilled subject matter experts to develop a detailed TDP template as a foundation for DMDII's project objective to produce 3D PDF TDP's. Recipes (i.e. software settings) were established in ACW to import the native CAD models (e.g. NX or Catia) and model characteristic inspection data (i.e. Excel spreadsheet), apply transformation actions to make the data fit-for-purpose and then publish to the 3D PDF TDP template. The recipe and templates were then deployed to Anark Core Server (ACS), which enables automated TDP production across the model based enterprise (MBE).

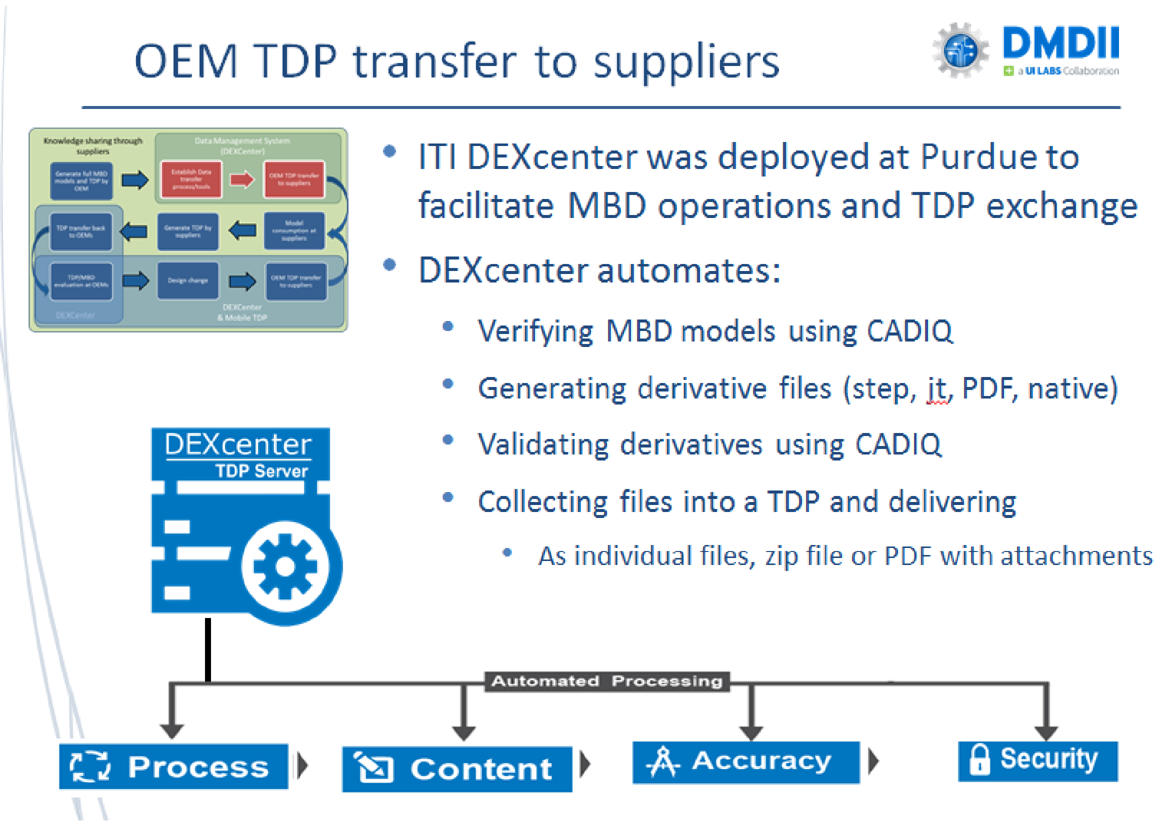
The published 3D PDF TDP provided means to review the document's details, visualize and interrogate the 3D MBD model, present model inspection characteristics and capture First Article Inspection (FAI) results. The PDF cover page is a consolidated checklist showcasing the type, format, contents, and other necessary information to provide an overview of the TDP. Page 2 focuses on the MBD model and integrates intelligent cross-referencing with the bill of characteristics and parts list and offers easy model view selection. Finally, the display of integrated FAI characteristic data starts on page 3 and fields for manual inspection results input are provided.

C. Data transfer process/tools

Early on in the project, Catia neutral data was manually translated by Lockheed Martin because the DEXcenter and CAD licensing was not completely ready at Purdue yet. The STEP AP203 and AP242 files were created directly from CATIA V5 internal translation. JT File was manually generated using Theorem Solutions “JT Translator”. The First Article inspection document and notes were created in excel per standard Lockheed Martin process. Two transmittal documents were also created, one in a typical Lockheed Martin format which utilizes PDF and one in Purdue format utilizing excel. The manually translated data was validated ITI CADIQ. Later in the project, the software/licenses were ready and capable to perform the CATIA translations and validations.

Similarly, the initial STEP AP203 and AP242 were exported directly from NX data. JT data was also generated from directly NX data, instead of a third-party translator. Rolls-Royce generates definition notes directly in the MBD, as opposed to an ancillary note document. Once DEXcenter was configured, translations and validations were done from NX9 and 11 to STEP AP203/242, PDF and JT.

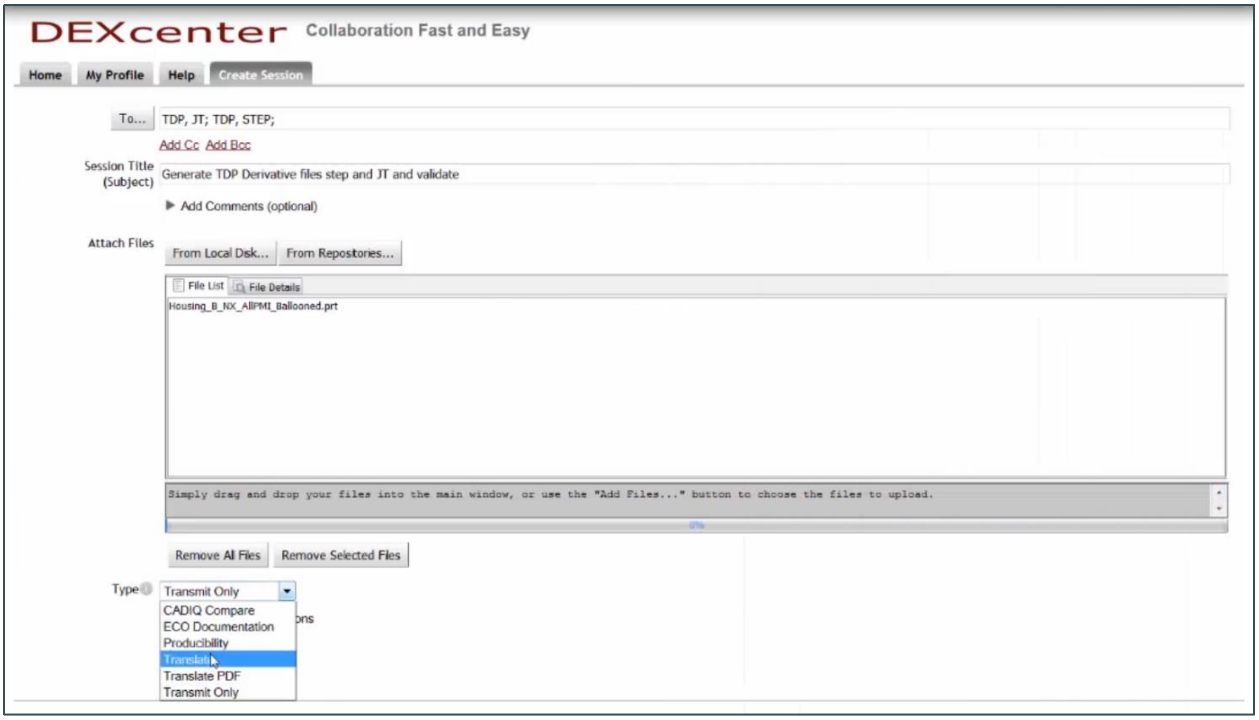
To support this project, ITI deployed DEXcenter and CADIQ at Purdue. DEXcenter is an enterprise web infrastructure which provides several major capabilities related to MBE/TDP procedures (Figures 11 and 12):



OEM TDP transfer to suppliers

- ITI DEXcenter was deployed at Purdue to facilitate MBD operations and TDP exchange
- DEXcenter automates:
  - Verifying MBD models using CADIQ
  - Generating derivative files (step, jt, PDF, native)
  - Validating derivatives using CADIQ
  - Collecting files into a TDP and delivering
    - As individual files, zip file or PDF with attachments

Figure 11: DEXcenter transfer



To...: TDP, JT; TDP, STEP;

Session Title (Subject): Generate TDP Derivative files step and JT and validate

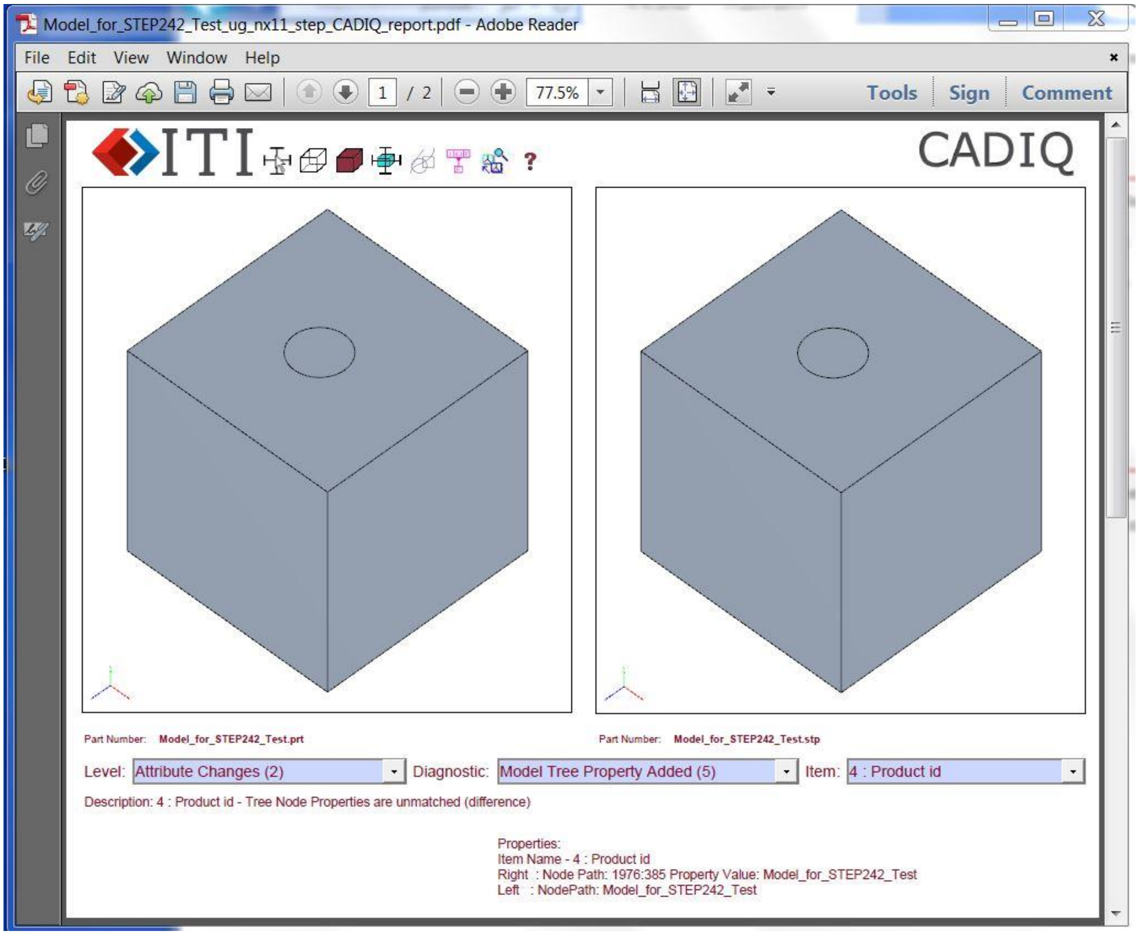
Attach Files: Housing_B_NX_AllPMI_Ballooned.prt

Simply drag and drop your files into the main window, or use the "Add Files..." button to choose the files to upload.

Type: Transmit Only

Figure 12: DEXcenter Session

1) DEXcenter provided a secure file exchange mechanism for the project team. User accounts for the team members were created on DEXcenter to allow easy exchange of large CAD files between participants.
    a. DEXcenter provides mechanisms to ensure that Intellectual Property (IP) protections are in place when exchanging files. DEXcenter can be configured to maintain records of Proprietary Information Agreements and checks that those are valid before data files can be sent.
    b. DEXcenter provides mechanisms to ensure Export Compliance procedures are followed. When conditions warrant (such as a transfer to someone outside the US), DEXcenter requires users to enter ECCN or ITAR codes along with any export license information if required.
2) DEXcenter provides automation capabilities of the various CAD applications involved. Specifically for this case DEXcenter has been configured to automatically execute NX 11, Catia V5-6R2017, Anark Core, and ITI's CADIQ products to process the MBD data. The resulting automated functions have been configured on the Purdue DEXcenter and were used during the project:
    a. Producibility analysis. Using CADIQ and the CAD system (NX or Catia), CADIQ can verify if there are any issues in the native model geometry or annotation which may cause a problem either using the native model directly or generating derivative files.
    b. STEP file generation. DEXcenter invokes NX and Catia to generate STEP files. STEP files can be any available STEP AP (203, 324, 242) which the corresponding CAD system can generate. The same functionality which allows control of the STEP file contents when using the translator interactively can also be configured for via the automated DEXcenter process.
    c. STEP file validation. DEXcenter invokes CADIQ with the CAD system to validate that the native CAD model and the derived STEP model are equivalent or identifies differences if they are not. The resulting CADIQ results are available in text, a proprietary CADIQ viewer, or 3D PDF format. The graphic reports show side by side comparison of a test model with issue identified (Figure 13). See lessons learned section for additional information about STEP AP242 validation compare.



Part Number: Model_for_STEP242_Test.prt

Part Number: Model_for_STEP242_Test.stp

Level: Attribute Changes (2) Diagnostic: Model Tree Property Added (5) Item: 4 : Product id

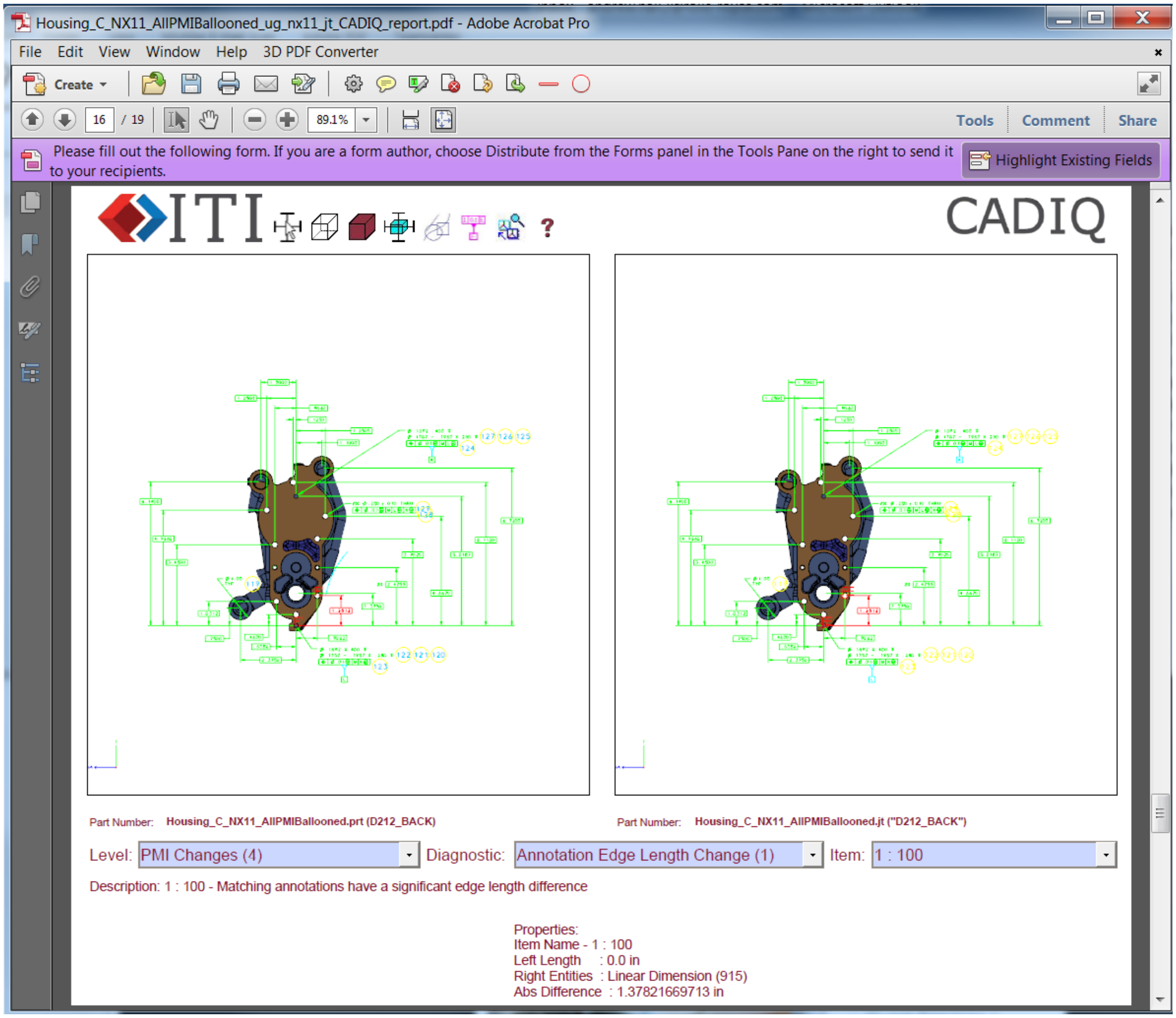
Description: 4 : Product id - Tree Node Properties are unmatched (difference)

Properties:
Item Name - 4 : Product id
Right : Node Path: 1976:385 Property Value: Model_for_STEP242_Test
Left : NodePath: Model_for_STEP242_Test

Figure 13: CADIQ STEP file Validation

The validation can be performed automatically as part of the STEP file generation or as an independent process. Specific aspects of the model to evaluate are configurable.

d. JT file generation. DEXcenter was configured to allow generation of JT files from NX. It was not configured to generate JT files from Catia. However it could have been. For generation of a JT file from NX, DEXcenter invokes the NX JT translator. The contents of the JT file are determined by the JT Translator configuration options.
e. JT file Validation. DEXcenter invokes CADIQ with the CAD system to validate that the native CAD file and the derived JT file are equivalent or to identify differences when they are not. As with the STEP validation, the specific aspects to validate are controlled by a CADIQ configuration. Figure 14 shows the validation result comparing the NX11 and JT data. The Pump Body Housing showed differences with geometry and PMI that required rework to correct, to avoid miscommunication of design requirements to supply chain.



Please fill out the following form. If you are a form author, choose Distribute from the Forms panel in the Tools Pane on the right to send it to your recipients.

Part Number: Housing_C_NX11_AllPMIBallooned.prt (D212_BACK)

Part Number: Housing_C_NX11_AllPMIBallooned.jt ("D212_BACK")

Level: PMI Changes (4)

Diagnostic: Annotation Edge Length Change (1)

Item: 1 : 100

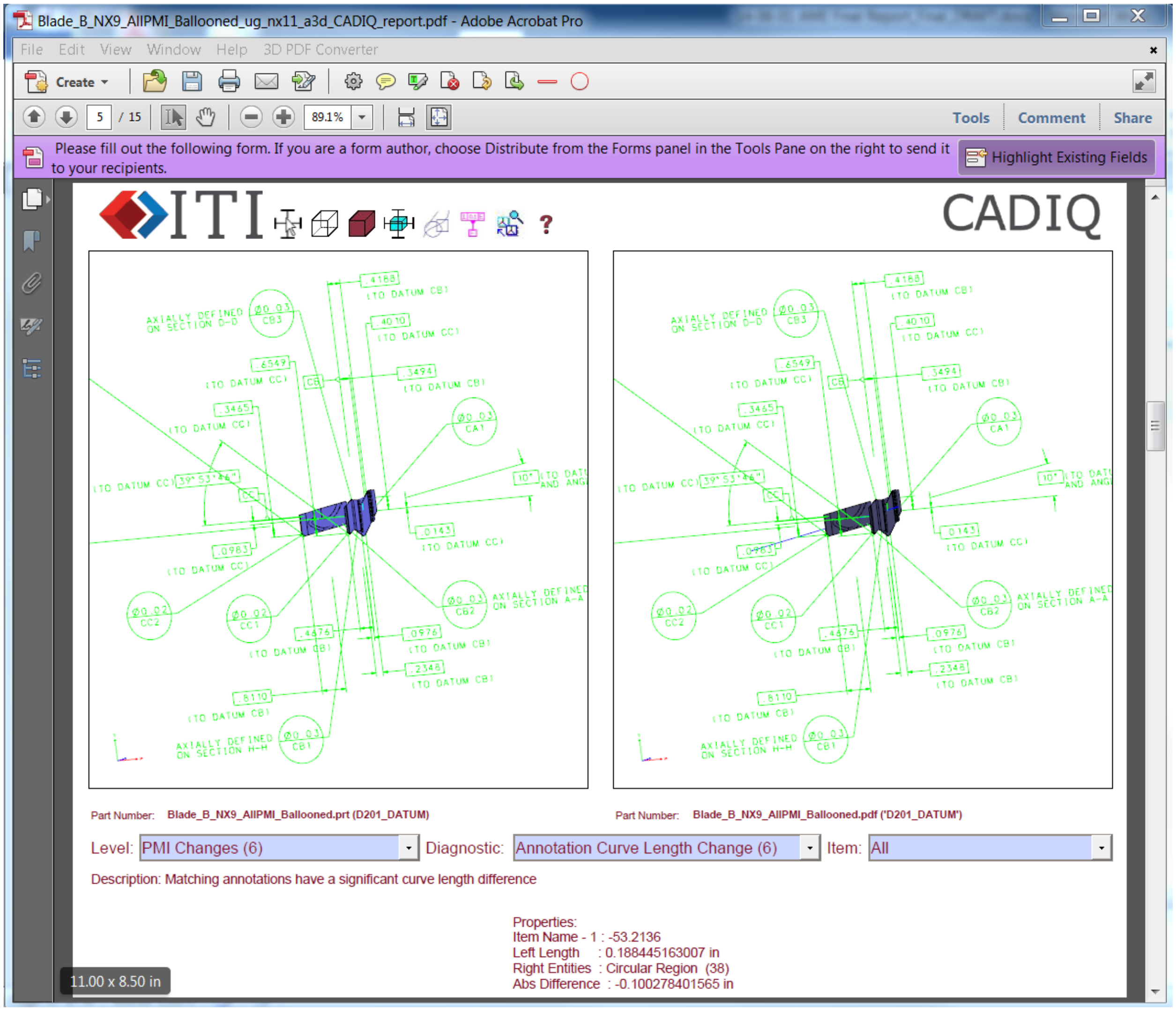
Description: 1 : 100 - Matching annotations have a significant edge length difference

Properties:
Item Name - 1 : 100
Left Length : 0.0 in
Right Entities : Linear Dimension (915)
Abs Difference : 1.37821669713 in

Figure 14: NX11 and JT Validation

f. 3D PDF file generation. DEXcenter invokes Anark Core Server to generate 3D PDF derivative files from native CAD files. This was configured and used for generation of 3D PDF files from NX.

g. PDF file Validation. DEXcenter invokes CADIQ with the CAD system to validate that the native CAD file and the derived PDF file are equivalent or to identify differences when they are not. As with the STEP validation, the specific aspects to validate are controlled by a CADIQ configuration. The validation can be part of the operation to generate the 3D PDF file or can be performed separately. Figure 15 shows the validation result comparing the NX11 and PDF data. The RR blade definition had issues with extra planes overlapping geometry (not shown) that required improving the data structure to allow for proper translation.



Blade_B_NX9_AllPMI_Ballooned_ug_nx11_a3d_CADIQ_report.pdf - Adobe Acrobat Pro

Please fill out the following form. If you are a form author, choose Distribute from the Forms panel in the Tools Pane on the right to send it to your recipients.

Part Number: Blade_B_NX9_AllPMI_Ballooned.prt (D201_DATUM)

Part Number: Blade_B_NX9_AllPMI_Ballooned.pdf ('D201_DATUM')

Level: PMI Changes (6)

Diagnostic: Annotation Curve Length Change (6)

Item: All

Description: Matching annotations have a significant curve length difference

Properties:
Item Name - 1 : -53.2136
Left Length : 0.188445163007 in
Right Entities : Circular Region (38)
Abs Difference : -0.100278401565 in

Figure 15: NX11 and PDF Validation

h. ECO Documentation. When 2D drawings were the master identification of a part or assembly, Engineering Change Orders (ECO's) were typically made by marking up the 2D drawing. With 3D MBD models, a new process is required. The DEXcenter ECO Documentation process allows 2 native CAD models (either NX or Catia) to be compared and then generates a report (as before a text, proprietary CADIQ viewer, or 3D PDF format) to explicitly identify the differences between the two models. This process uses both CADIQ and the CAD system.

3) Controlling automated applications

The various CAD applications are all complex and provide uses with many options. It is critical to achieving the intended result that the appropriate options be utilized across the set of applications being used. DEXcenter provides a means to specify and manage the appropriate application options.

   a. STEP options - There are numerous options related to generating and using STEP files. Here are a few of the most significant options which are available in creating STEP files:
      i. STEP AP. STEP provides numerous Application Protocols (APs) which are appropriate for exchanging CAD data. AP203 and AP214 provide for geometry exchange and with the extended versions graphical PMI exchange. AP242 is the newly developed AP which provides both semantic (functional) and graphic PMI. In this project in exchanging data between NX and Catia, it was not useful to use AP242 since both applications did not support semantic PMI in AP242
         1. CAD systems include many types of entities such as solid bodies, surfaces, wireframe, PMI, etc. The use cases for the exchange dictate the types of entities which need to be transferred. In most cases, solid bodies and PMI are all that is required and desirable.
         2. Visibility / layers / other. CAD systems typically provide a mechanism to organize data through different parameters such as visibility and layers. This is frequently used to separate construction geometry from final geometry. In most cases, it is desirable to only include the final geometry and not the construction geometry.
   b. JT options - options for generating JT files are similar to those of STEP except there is no AP to be considered. However entities, visibility, etc. are pertinent.
      i. 3D PDF - options for generating 3D PDF files from CAD models are again similar to those of JT and STEP with respect to entities and organization. A PDF file is typically generated from a template. Using a different template can provide a different look.
      ii. CADIQ Validation options - CADIQ provides dozens of validation options. Typically not all validation options are desirable though. There are two major considerations when specifying the CADIQ options: consistency with the source / target files, and criticality to the use case.
         1. Consistency: CADIQ validates different types of data. CADIQ should only validate the entities expected in derivative files. If you choose to export solid bodies to step but not surfaces, then CADIQ should only validate the solid bodies not surfaces.
         2. Criticality: CADIQ inspects models very thoroughly. Some of the issues identified by CADIQ though may not be relevant or important to the intended Use Case. Usually these diagnostics are disabled to prevent generating a large amount of data which makes recognizing the important data more difficult.

4) TDP Generation. As part of the file transmission capability, DEXcenter provides the ability to package the various files needed in the TDP into a zip or PDF file. The PDF file can have an automatically generated manifest using information about the files included.

D. OEM TDP transfer to suppliers

Upon completion of translation and validation of each of the MBD models and derivatives using DEXcenter, the TDPs were then transferred to supply chain (upper level OEM: Lockheed Martin; mid-level OEM Rolls-Royce; suppliers: 3rd Dimension, Zeiss, Purdue University [acting as supplier]. Transmittal via DEXcenter allows for tracking of the TDP data and sharing with multiple team members. The TDP supply chain flow (Figure 16) was established to simulate real-world. Lockheed Martin sent the Bulkhead TDP to Rolls-Royce to design Pump Body Housing. Rolls-Royce provided the Pump Body Housing design iterations to Lockheed Martin for consideration into Bulkhead. Rolls-Royce also sent the Pump Body Housing to 3rd Dimension to have a part additive manufactured. The Pump Body Housing was also provided to Zeiss Corporation for inspection. The other TDP data was sent to Purdue to test capabilities of various CAD systems (NX9 & 11, Catia V5 R24 & R26, Solidworks 2017) and file formats (PDF, JT, STEP, 3MF, STL).

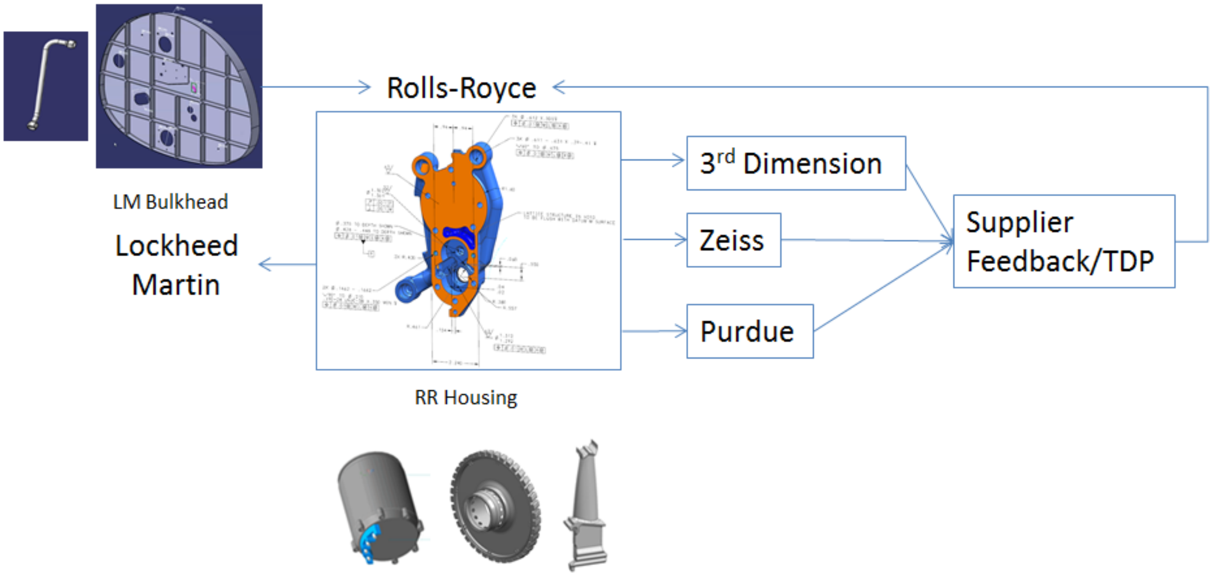


Figure 16: TDP Supply Chain Flow

E. Model consumption at suppliers

The consumption of MBD by suppliers can be “human-read” and “machine-read” data. Meaning, can a human read all of the information in the files provided adequately to perform their task. Or does a machine read the data directly, in effect removing the human from being required to interpret the definition to input data into the machine/software. Consideration for both methods was given, because a real-life supply chain may not be able to consume the MBD as “machine-read”, as was the case with additive manufacturing technology that still relies on human interpretation to input specific product data. In some cases, “human-read” has to supplement or confirm the “machine-read” information.

1) Neutral file (STEP, JT PDF) consumption/transfer among NX, Catia, other systems

Lockheed Martin downloaded the STEP AP203 and AP242 models from Purdue’s DEXcenter that were created by Rolls-Royce for the pump body housing. Using the Functional Tolerance & Annotation (FT&A) workbench, LM read and imported the STEP files into CATIA V5. In CATIA V5 the STEP AP203 file displayed the captures, views, dimensions and notes which were generated by NX11’s PMI capability. The imported PMI was then manipulated by the CATIA V5 FT&A workbench to filter various PMI to support viewing. Additional results are noted in the Lessons Learned section below.

Rolls-Royce retrieved the Lockheed Catia, STEP, JT and PDF data from DEXcenter. The data was reviewed in respective software and results recorded (see Lessons Learned section).

Purdue retrieved all of the project data from Lockheed Martin and Rolls-Royce to simulate consumption by supply chain. Creation of MBD Technical Data Packages requires a significant number of translations throughout the lifecycle. To ensure that each of these translations was producing quality data, the Purdue team performed validation after each translation. This essentially is a comparison of the translated model to the source model. The model was translated out of NX9 and 11. The translations were manually assessed using various CAD software such as, Solidworks, Catia R24, and R26. The results of the validation efforts are included in the Model Evaluation at OEM section. One format stood out in the validation process, STEP AP203, but even AP203 has shortcomings. It is important that any organization looking to adopt a MBD TDP framework to assess its own capabilities.

2) Additive manufacturing consumption

3rd Dimension consumed the PDF and STL data to run the additive manufacturing process on the Rolls-Royce Pump Body Housing (Figure 17). They were not able to consume the 3MF format into their process to make the part. The 3MF data does not support PMI information at this time. Primarily 3MF data only supports material and color information. Therefore the annotation was viewed via the PDF file. However, we were able to view the 3MF file in Microsoft 3D Builder application. 3rd Dimension demonstrated their capability to manufacture the pump body housing which, while not directly consuming the MBD, did demonstrate that a MBD/TDP is sufficient for additive manufacturing. 3rd Dimension also performed an optical scan of the manufactured part and provided the scan data to Rolls-Royce.

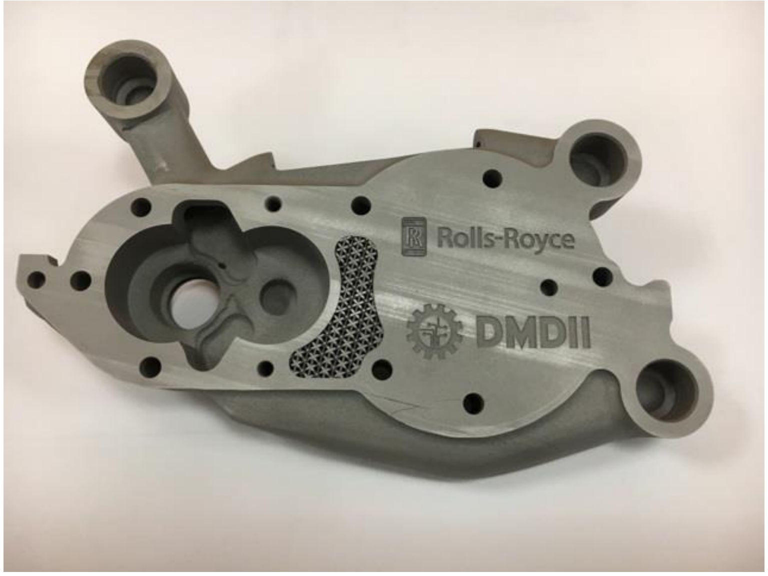


Figure 17: Additive Manufacturing of Pump Body Housing

Purdue evaluated additive manufacturing technology ability to consume a new file format (3MF) introduced during the project. The 3MF (3D Manufacturing Format) enables 3D printing by utilizing full-fidelity 3D models, in place of traditional STL format in use today. This project set a sub-goal which evaluated the feasibility of this software to support additive manufacturing process. Figure 18 and 19 describes the translation processes to move models into 3MF. These two workflows were assessed after completion of the translations.

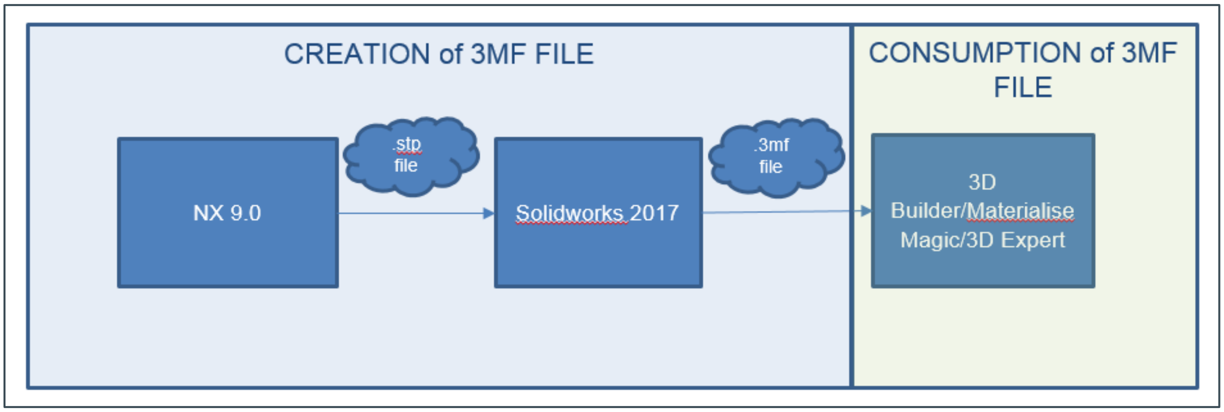


Figure 18: NX to Solidworks to 3MF

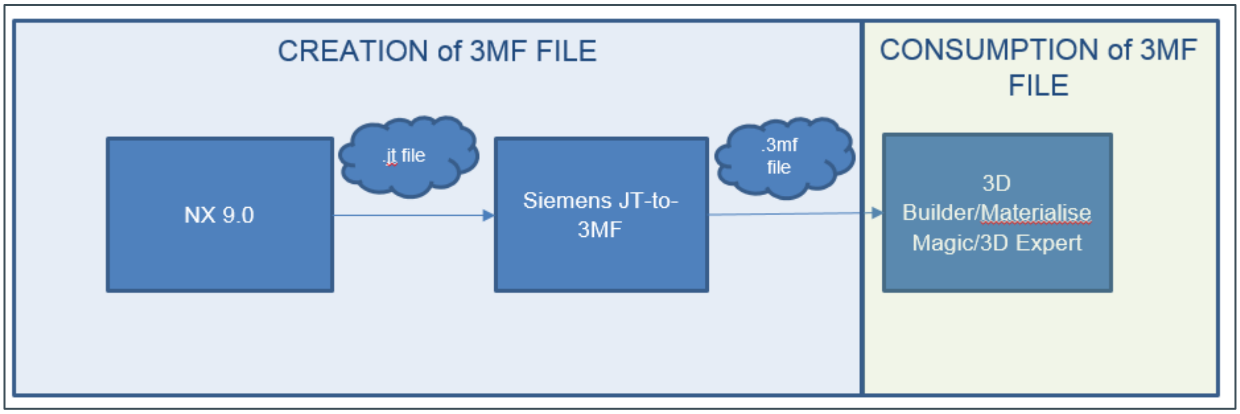


Figure 19: NX to JT to 3MF

The results of this process are:

- Loss of PMI while importing both NX .prt and .stp files into Solidworks 2017.
    - A standalone application by Dassault Systemes called eDrawings is used to read STEP AP 242.
- The 3mf files created from SolidWorks 2017 did not contain PMI.
- The 3mf files created from the JT-to-3mf also did not contain PMI.

3) CMM Inspection consumption

For MBD related to quality and dimensional inspection, the project evaluated multiple methods to consume PMI in the inspection process.

These methods were compared to traditional methods to generate measurement plans on a CMM. Traditional methods typically involve a CMM programmer importing a CAD file (with no PMI) and reading a hard copy blueprint to build a CMM measurement plan. These methods are subjected to the following faults.

- Different CMM programmers may have different interpretation of the print
- Time consuming to find and evaluate the proper feature of the part to be measured
- Time consuming to find and identify datums
- Time consuming to build the dimension and characteristics that make up the measurement plan
- Risk of data entry errors when entering tolerance information into the measurement program
- Management, printing, revision control of paper drawings especially with multiple pages

For this project, a ZEISS Prismo CMM (Figure 20) equipped with CALYPSO software was used. To consume PMI, CALYPSO requires the specific software (e.g. NX or CATIA) PMI option to read the native CAD file. The following benefits were found when importing native CAD models with semantic PMI into the CMM software.

Figure 20: Zeiss Prismo Inspection

a. Significant time savings in creating the measurement plan.
    i. Estimated 80% time saving when compared to traditional methods to create a measurement plan.
    ii. CALYPSO allows the user to simply double click the PMI and the software automatically creates the measurement plan including:
        1. Extracting the required features to be measured
        2. Extracting the required datum reference frame
        3. Extracting the tolerance including classification of fits
        4. Defining the dimensional characteristics
        5. Applying the optimal measurement strategy including scanning paths, speeds and point density
        6. Generating the appropriate navigation path around the part for each measured feature
        7. Assigning the appropriate measuring styli and orientation for rotating heads
    iii. Additional time savings can be found by allowing the user to build an entire measurement plan from all PMI or by selected specific CAD PMI views. This further reduces time by eliminating the need to double click each PMI.

b. More consistent and more accurate measurement plans are generated between different CMM programmers.
    i. Because different CMM programmers vary in training and experience, they apply different inspection methods, techniques, opinions, and interpretation of dimensions. Because of the automation, using semantic PMI reduces or in some cases eliminates the variation that typically comes from different CMM programmers.
    ii. Consuming the PMI removes the errors from manually entering tolerance information; reduce errors from incorrectly selecting the wrong datum reference frame, incorrectly selecting the wrong feature to measure, etc.

c. Reduce the training requirements for CMM programmers
    i. Because of the automation of creating the measurement plan, less training is required in the following areas:
        1. Operation and use of the inspection software
        2. Blueprint reading
        3. Understanding and applying GD&T

d. Consuming the PMI in the OEM CMM software provides a more accurate measurement and improves performance of the CMM.
    i. Relative to importing DMIS programs that are built with PMI and imported the DMIS program into the CMM software, the benefits of consuming the semantic PMI directly in the OEM CMM software include:
        1. The OEM CMM software understands the system capability and applies the optimal scanning strategy path, speed, point density and styli to provide the most accurate and fastest measurement. For example, the ZEISS CMM qualifies the rigidity of the styli and adjusts the speed appropriately for optimal accuracy and speed.
        2. Removes the uncertainty and issues related to two translation steps; post processing to DMIS and then translation into the CMM software.

F. Generate TDP by suppliers and transfer back to OEM

Lockheed Martin revised the original design for the attachment of the pump assembly to the bulkhead. Fastener size was increased requiring the hole sizes to change. The parameters of the holes were revised and the hole size geometrically was updated. The PMI that was semantically linked to the hole features in the bulkhead which was automatically updated with the change. New STEP models with the change incorporated and change management documents were submitted to show the new hole size. A revised technical data package (TDP) was created with all the essential data and submitted to DEXcenter for vendor consumption.

As mentioned in previous section, 3rd Dimension provided the scan results as part of their return TDP to Rolls-Royce. There were noted issues during the scan that were communicated to Rolls-Royce via a marked PDF.

Zeiss communicated necessary PMI updates to Rolls-Royce to improve consumption of the MBD into Calypso software.

The revised TDP data or communication was provided to Rolls-Royce/Lockheed Martin through DEXcenter or traditional communication methods (e.g. email) for updates to the pump housing/bulkhead.

G. Model evaluation at OEMs

As CAD and derivative data was generated by OEM and supplier, and sent from OEM-to-Supplier or Supplier-to-OEM, the translated data was compared to original data using DEXcenter/CADIQ and manual, visual comparison. The results for each comparison are provided in Appendix A.

There were 3 main levels of results for the use cases: Level 1 OEM (Lockheed Martin) to Level 2 OEM (Rolls-Royce), Level 2 OEM (Rolls-Royce) to Supplier (3rd Dimension, Zeiss, Purdue) and Level 2 OEM (Rolls-Royce) to Level 1 OEM (Lockheed Martin).

Comparison was performed to evaluate the integrity of the data being supplied. Verifying the original CAD geometric model data translated properly to each of the derivatives, the PMI annotation translated without miscommunication of intent and the PMI retained its semantic associativity to geometry. CADIQ was used to perform the automatic comparison from CAD (NX and Catia) to derivative (STEP, 3D PDF, JT). Visual comparison was done in various CAD, inspection and visualization software: NX, Catia & Solidworks (CAD), Calypso (inspection), 3D Builder & 3D Expert (3MF), Teamcenter Visualization (JT), Adobe Reader (PDF), Microsoft Word, Excel.

H. Mobile TDP visualization

Mobile visualization is an important aspect of working with MBD data. Availability of the 3D data at point-of-use (e.g. shop floor) is an important aspect of supply chain adoption, considering there is no 2D drawing data. The project demonstrated consumption of the MBD in PDF, JT and HTML5 formats. These were viewed on Microsoft Surface tablets and include the ability to markup and provide comments on the MBD data to communicate within the supply chain.

The Microsoft Surface tablets used for this joint venture run Windows 10 and the desktop version of Adobe Acrobat Reader (or Professional). The 3D PDF TDP's are fully compatible with the tablets and provide the same functionality as on a similarly equipped desktop computer. This enables a preferable alternative for performing shop floor and inspection operations over mainstream drawings and datasheets. However, due to limitations of the Adobe Acrobat Reader mobile app, 3D PDF documents are not compatible with other mobile device operating systems (i.e. Android, iOS, and Windows

Mobile); for complete platform compatibility, HTML5 TDP's via Anark MBEWeb is recommended.

I. Training Curriculum Design for MBD

The WBS tasks of "Consumption Specific Guidelines" and "Knowledge Sharing" are included in this section and the Lessons Learned. The training curriculum/tutorial designed as a result of this research focused on education of novices in regards to MBD technical data packages. Its primary purpose is to quickly introduce one to the breadth of knowledge that is related to model-based definition. It educates new users on terminology, process, and resources. Through the tutorial, one should be well equipped to begin work on converting to a model-based definition approach. However, it will not make them an expert, nor does it provide strict guidelines on how to achieve a model-based definition technical data package approach. Instead it provides a novice education, to support the understanding of a framework for Model-definition technical data packages. Refer to attached Purdue tutorial document.

V. LESSONS LEARNED

Lessons learned were identified based on the TDP/MBD Project Flow (Figure 1). The flow can be broken down into 5 basic concepts of MBD/TDP usage: Creation, Translation, Validation, Consumption and Training. The concepts may be repeated throughout the flow of a typical design. The Lessons Learned documented in this project are grouped according to those concepts of Creation, Translation, Validation, Consumption and Training. Many of the lessons show that there are needed improvements to software and standards to make MBD consumption more successful. Given the capabilities of software and standards as of the project, some of the limitations of success are due to existing capability. These are only limitations and do not make MBD unusable. Users need to be aware of their own specific software limitations. Industry needs to continue to provide input for improvements to software and MBD related standards.

A. Creation Lessons

1. Creation lessons as noted by Rolls-Royce
   a. PMI must be properly applied and associated to the respective geometry in order to communicate design intent. This means not using 2D drawing approach for defining part, but using features (e.g. cylindrical, planar faces, centerpoints and edges). For example, drawing dimensions would be applied from line to centerpoint to define location of a hole, thereby requiring consumer of drawing to interpret the full meaning. But MBD should rely on the geometry to fully define the requirements. So the same dimension in MBD would be applied from face to cylinder face, if attempting to control the orientation of both faces. Or edge to center, if relationship between faces is

not important. Design intent is critical to be properly defined to remove given that goal of MBD is to reduce or remove human interpretation.

   b. Along the same lines of applying PMI properly, within NX there are several ways to create PMI that technically are the same for human consumption. But when consumed by downstream software (e.g. Zeiss Calypso inspection software), the PMI method (horizontal versus point-to-point; horizontal with added diameter symbol versus diametral) impacts how software interprets the requirement. If not applied with the proper method, the wrong requirement is communicated and could lead to re-work.

2. Creation lessons as noted by Siemens
   a. As of NX11, a functionality called "Wave Linking PMI" doesn't work with NX LightWeight sections. The views where the PMI is located are not available for selection. Therefore PMI cannot be displayed from component into assembly. As of NX10, NX "heavy" sections (as opposed to LightWeight) are being discontinued.

B. Translation Lessons

1. Translation lessons as noted by ITI
   a. The intent at the start of the project was to use STEP AP242 which includes semantic PMI capability to exchange models with PMI between Catia and NX. To do that, AP242 with semantic PMI capabilities must be available in both CAD systems (e.g. NX and Catia). NX 11 was the first release of NX to provide semantic PMI support in AP242. Catia V5-6R2017 provided AP242 support but only with graphical PMI not semantic PMI. Therefore functional PMI could not be exchanged between Catia and NX. Instead AP203 edition 2 which provides graphical PMI capability was used. The PMI in this case becomes notes and lines within the target CAD system instead of functional PMI. AP242 support with semantic PMI is planned for future Catia releases but those were not within the timeframe of this project. Companies need to evaluate their capabilities to write and read AP242. If AP242 is not functioning, then AP203 edition 2 for human consumption will need to be used.

   b. CADIQ needs to have the respective CAD software(s) installed on the system being used to perform the translation and validation of the STEP and JT data.

   c. When translating data from any given CAD software in CADIQ, "what" to translate (e.g. surfaces, datums, solids, PMI) depends on the specific consumption requirement. Different scenarios require varying data during translation for proper consumption. For example, translating datum planes may be too much data for a supplier. At a minimum, most software and human consumption needs to "read" solid and PMI data. Other data (e.g. curves, planes, surfaces) may need to be translated/validated to derivatives also.

d. To confirm translation of NX11 to STEP AP242, the STEP file can be imported back into the CAD system. It was discovered that the STEP file had to be an imported into NX, not simply opened in NX. Opening the STEP in NX fails to open the PMI and Model views.

e. It is critical when exporting CAD data to a derivative (e.g. STEP AP242) that the type of data (i.e. part versus assembly) be understood and the same between the two files that will be validated in later steps. If not, inaccurate or incomplete results could be provided. See further explanation in Validation lessons.

2. Translation lessons as noted by Lockheed Martin
   3MF file type for additive manufacturing will be supported in Catia V5-6R2017 and 3DEXP 2017.
   a. Scenario 1: CATIA V5 R26 Derived Results from STEP AP242 Translation
      i. STEP AP242 file must be derived from CATIA V5 R26 which is the minimum version to obtain 3D Annotations (PMI).
      ii. Conversion of derived STEP AP242 file back into CATIA V5 must be R26 plus have metric units as the default setting to display Functional Tolerance & Annotation (FTA). If inch units are used the Geometric Dimension & Tolerance (GD&T) frames, leaders etc. display, however, no 3D Annotation text appears (Figure 21). This is supposed to be fixed in the latest version of V5.

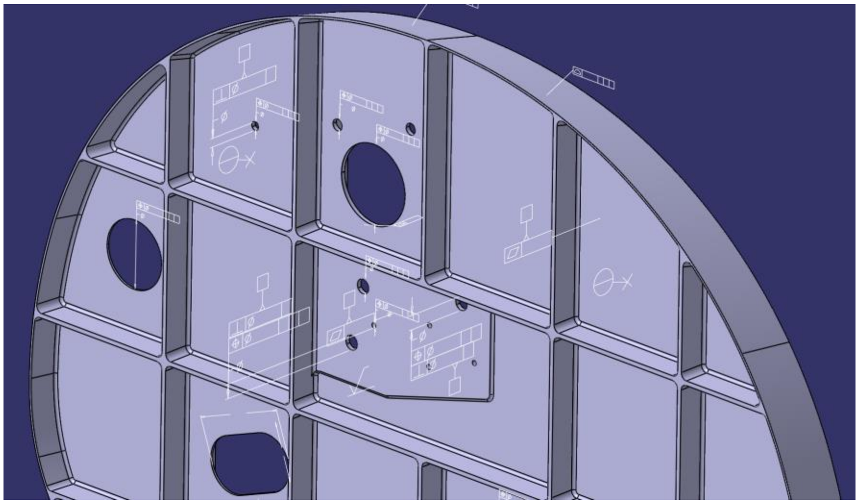


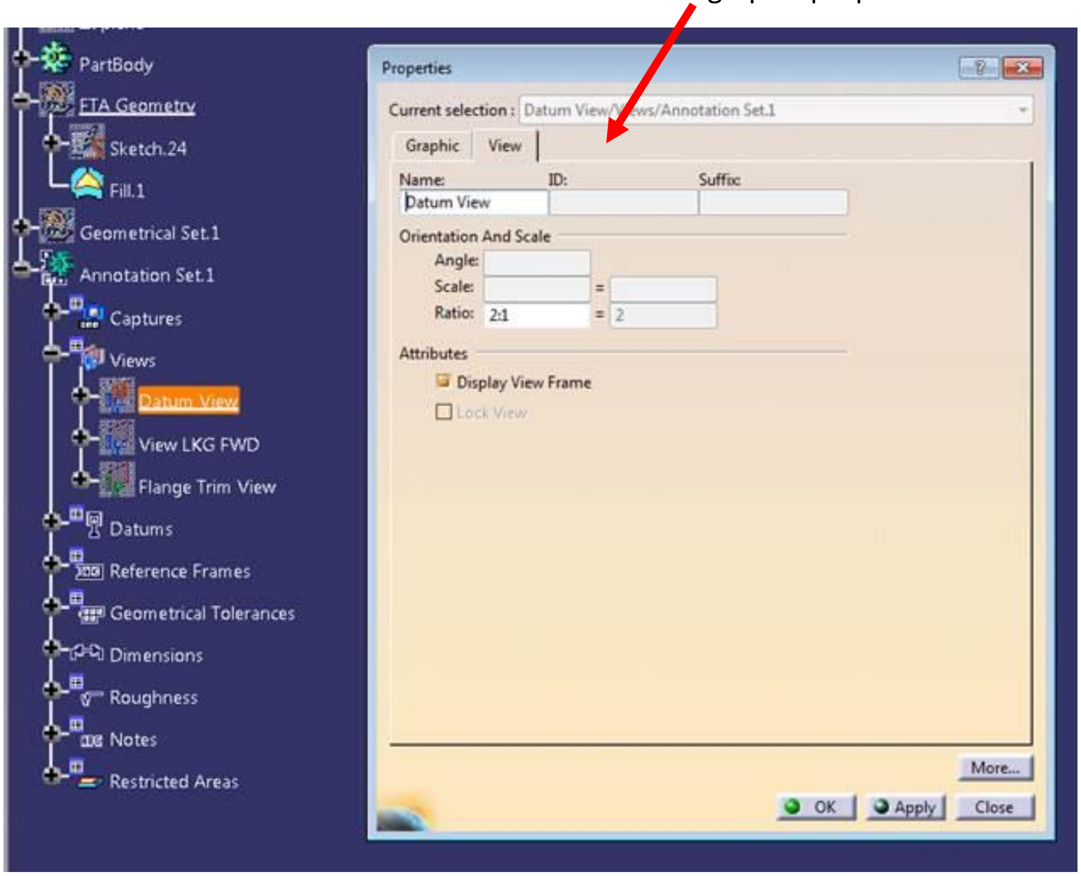
Figure 21: LM Bulkhead MBD

iii. CATIA Functional Tolerance & Annotation (FTA) license is required to show linked geometry to 3D Product Manufacturing Information (PMI) Annotation.

iv. FTA from derived STEP AP242 file cannot be moved or modified. It is visual only.

v. FTA differences in properties window (Figure 22).

FTA views in native CATIA V5 have a view and graphic properties tab.



Current selection : Datum View/Views/Annotation Set.1

Name: Datum View

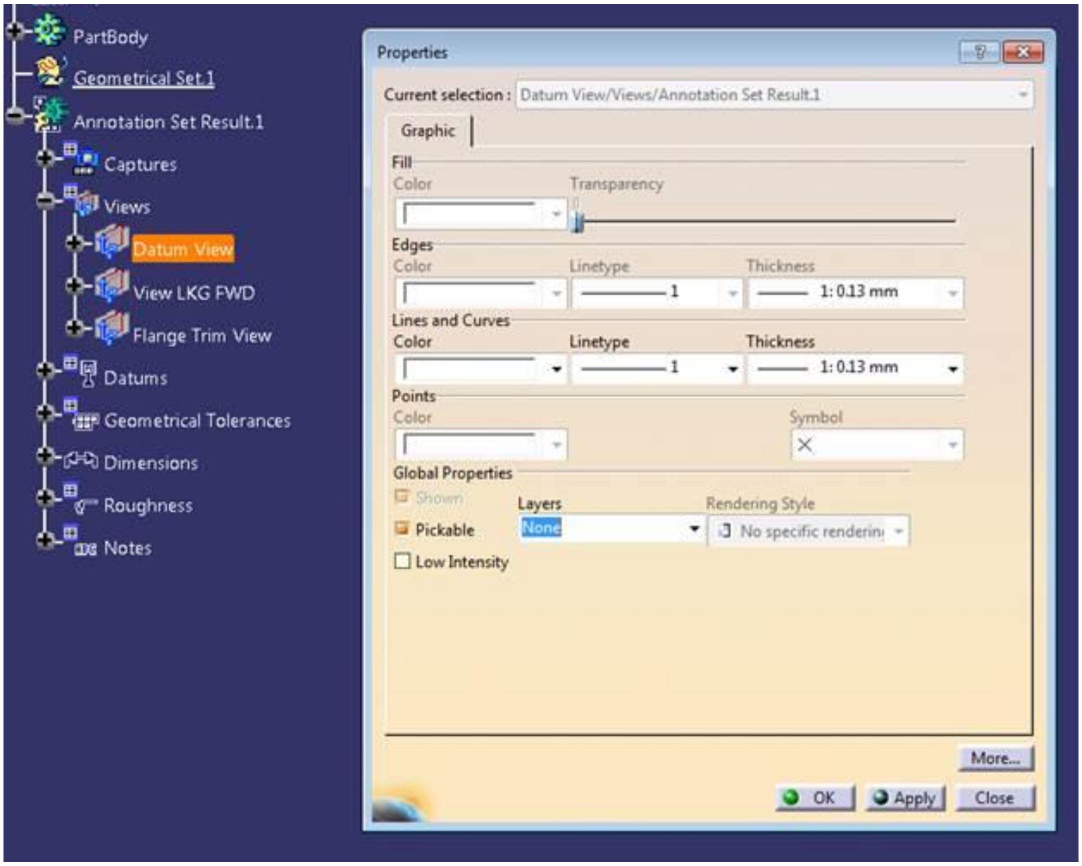
Ratio: 2:1 = 2

☑ Display View Frame

☐ Lock View

Figure 22: CATIA V5 FTA View

Models converted from STEP do not have a view tab only have graphic properties (Figure 23).



Current selection : Datum View/Views/Annotation Set Result.1

Fill: Color, Transparency

Edges: Color, Linetype 1, Thickness 1: 0.13 mm

Lines and Curves: Color, Linetype 1, Thickness 1: 0.13 mm

Points: Color, Symbol ×

Global Properties: ☐ Shown, ☑ Pickable, ☐ Low Intensity, Layers None, Rendering Style No specific renderin

Figure 23: CATIA V5 Properties

vi. Upon STEP AP242 file conversion back to V5, FTA 3D captures sometimes lose orientation and zoom.

vii. V5 PMI visualizes through solids as default. Other CAD tools do not allow visualization through solid by default.

viii. STEP AP242 files derived from CATIA V5 assembly data then converted back to CATIA V5 the CATPart PMI/FTA are visualized but not the Product PMI/FTA from the CATProduct.

b. Scenario 2: STEP AP242 files of Rolls-Royce Pump Body Housing imported from NX
   i. STEP AP203 file received from Rolls-Royce originating NX Data.
      1. Views are not named
      2. Appears to be an individual view for each piece of annotation
      3. Sections views from NX do not import/translate

    4. Models contain isolated axes

ii. STEP AP242 file received from Rolls-Royce originating NX Data.

    1. The initial STEP AP242 NX translated part was imported as a CATProduct (Figure 24 and 25). It did not contain an annotation set with PMI.

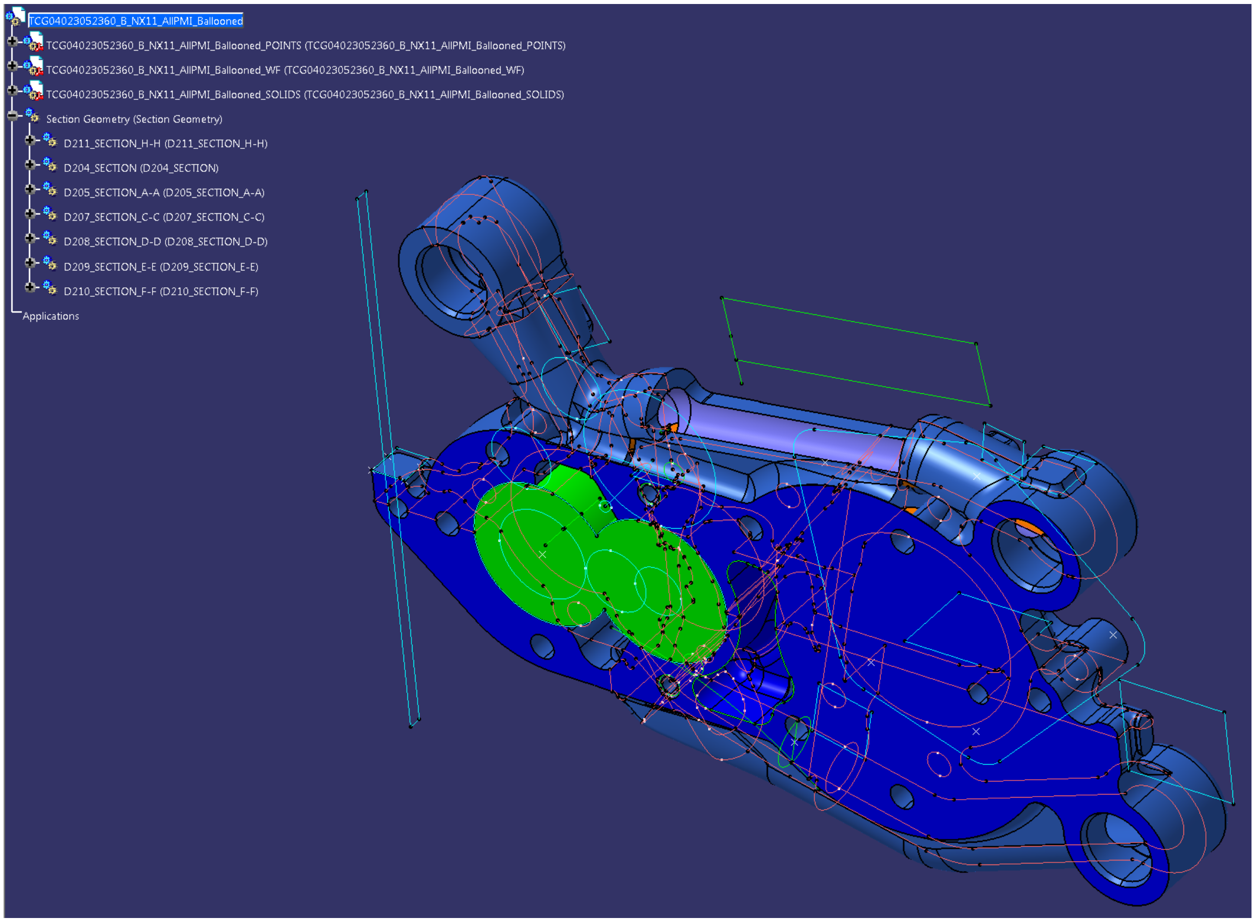
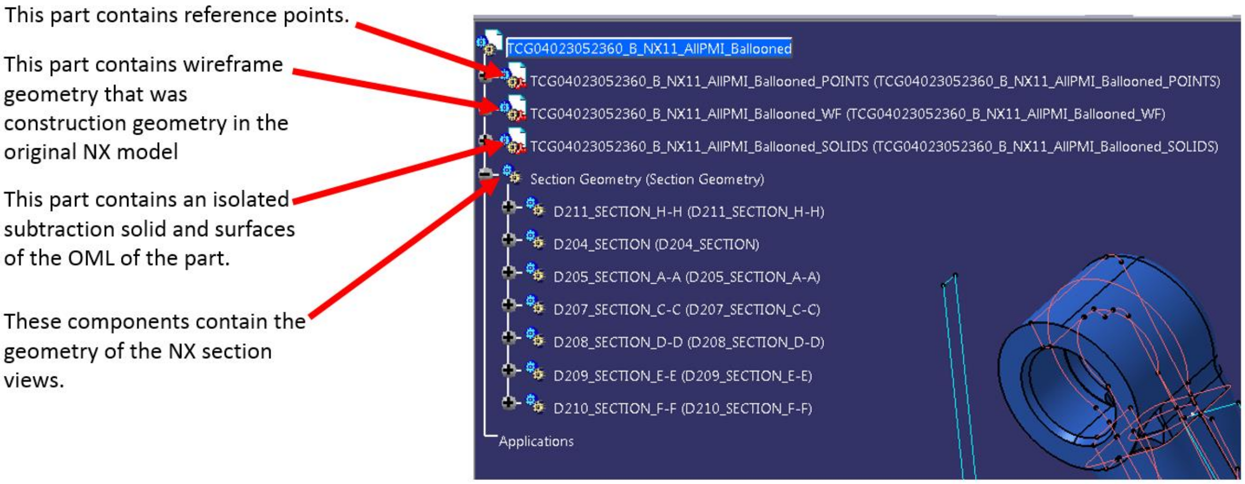


Figure 24: CATIA V5 STEP 242 Import #1


This part contains reference points.

This part contains wireframe geometry that was construction geometry in the original NX model

This part contains an isolated subtraction solid and surfaces of the OML of the part.

These components contain the geometry of the NX section views.

TCG04023052360_B_NX11_AllPMI_Ballooned
- TCG04023052360_B_NX11_AllPMI_Ballooned_POINTS (TCG04023052360_B_NX11_AllPMI_Ballooned_POINTS)
- TCG04023052360_B_NX11_AllPMI_Ballooned_WF (TCG04023052360_B_NX11_AllPMI_Ballooned_WF)
- TCG04023052360_B_NX11_AllPMI_Ballooned_SOLIDS (TCG04023052360_B_NX11_AllPMI_Ballooned_SOLIDS)
- Section Geometry (Section Geometry)
  - D211_SECTION_H-H (D211_SECTION_H-H)
  - D204_SECTION (D204_SECTION)
  - D205_SECTION_A-A (D205_SECTION_A-A)
  - D207_SECTION_C-C (D207_SECTION_C-C)
  - D208_SECTION_D-D (D208_SECTION_D-D)
  - D209_SECTION_E-E (D209_SECTION_E-E)
  - D210_SECTION_F-F (D210_SECTION_F-F)
- Applications

Figure 25: CATIA V5 STEP 242 Import #1

2. The second attempt of STEP AP242 NX translated part was imported as a CATPart (Figure 26 and 27). It does contain an annotation set with partial PMI. The notes came over. But, there is no annotation related to the part.
   i. Contains Views for each piece of annotation.
   ii. None of the original views.
   iii. No captures.
   iv. Missing an extensive amount of the original annotation.

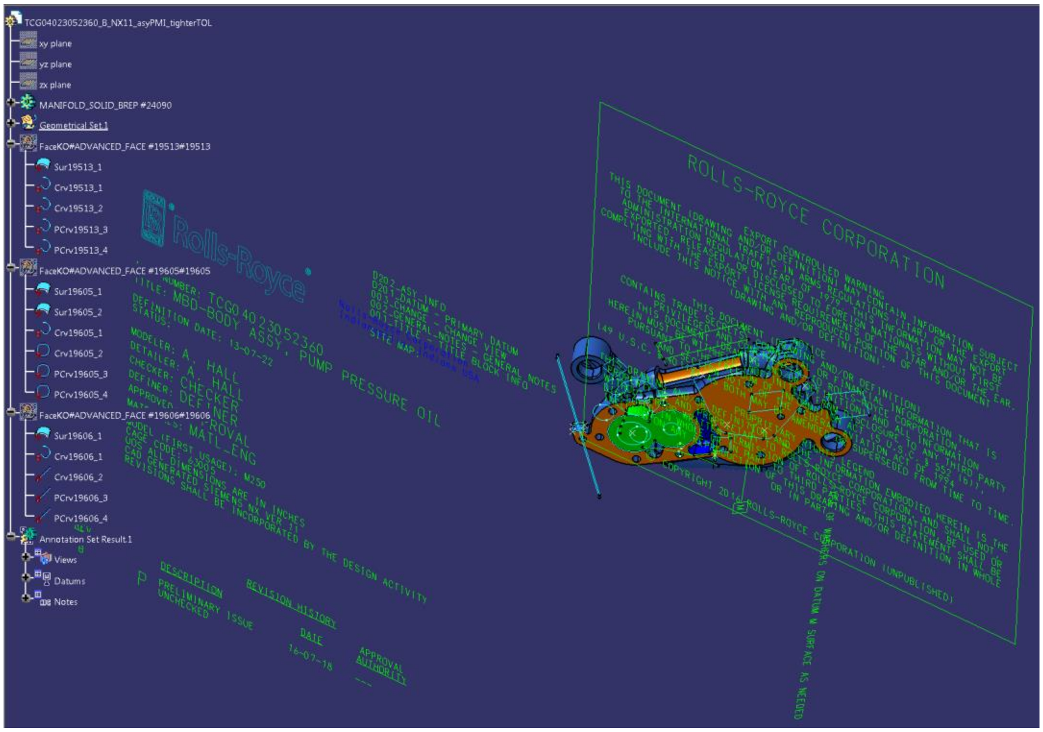

TCG04023052360_B_NX11_asyPMI_tighterTOL
- xy plane
- yz plane
- zx plane
- MANIFOLD_SOLID_BREP #24090
- Geometrical Set.1
- FaceKO#ADVANCED_FACE #19513#19513
  - Sur19513_1
  - Crv19513_1
  - Crv19513_2
  - PCrv19513_3
  - PCrv19513_4
- FaceKO#ADVANCED_FACE #19605#19605
  - Sur19605_1
  - Sur19605_2
  - Crv19605_1
  - Crv19605_2
  - PCrv19605_3
  - PCrv19605_4
- FaceKO#ADVANCED_FACE #19606#19606
  - Sur19606_1
  - Crv19606_1
  - Crv19606_2
  - PCrv19606_3
  - PCrv19606_4
- Annotation Set Result.1
  - Views
  - Datums
  - Notes

Figure 26: CATIA V5 STEP 242 Import #2

This solid is the subtraction solid (of impellers) in NX.

This geometrical set contains surfaces of the part OML.

These sets contain junk wireframe.

The annotation set contains the part notes. But, it seems to not have any PMI that was associated with the solid.

Figure 27: CATIA V5 STEP 242 #2

   3. Some issues with issues with NX translation could be due to settings in NX.

3. Translation lessons as noted by Anark

   a. Due to the current limitations of the Adobe Reader, 3D PDF TDP's encountered some limitations, such as platform compatibility and performance of large models. HTML5 TDP's published with Anark MBEWeb do not suffer from these limitations. The same Anark Core recipe-based publishing process can be used to publish to HTML5 Templates. In fact, a single recipe can publish to both 3D PDF template and HTML5 templates enabling a dual-format automated deployment strategy.

   b. 3D PDF and HTML5 formats produced by the Anark Core platform offer many advantages for the TDP application, particularly in the context of supply chain communication and collaboration:

- Both formats support incorporation of technical 3D data in the context of structured interactive documents
- Both enable complex app-like functionality that can be tailored to individual use case requirements

- Both offer packaging and compression of a variable amount of associated documents
- Both provide cross-platform compatibility
- Barriers to use are low; no more than the free Adobe Acrobat Reader software or a free web browser are needed to view and interact with the published documents
- 3D models can be emphasized and easily interrogated using manual investigation or automated presentation facilitated by predefined views and intelligent cross-referencing with metadata
- Multiple streams of authoritative data may be easily integrated and presented effectively

c. As a result of these advantages, 3D PDF and HTML5 were chosen over the STEP and JT as the container for organizing the 3D TDP and its contents.

d. Creation of 3D PDF data is best configured with one CAD system per set of templates and project files. This is due to the number of CAD-specific attributes and differing methods of PMI application. This may require using multiple templates/project files to translate data.

4. Translation lessons as noted by Rolls-Royce

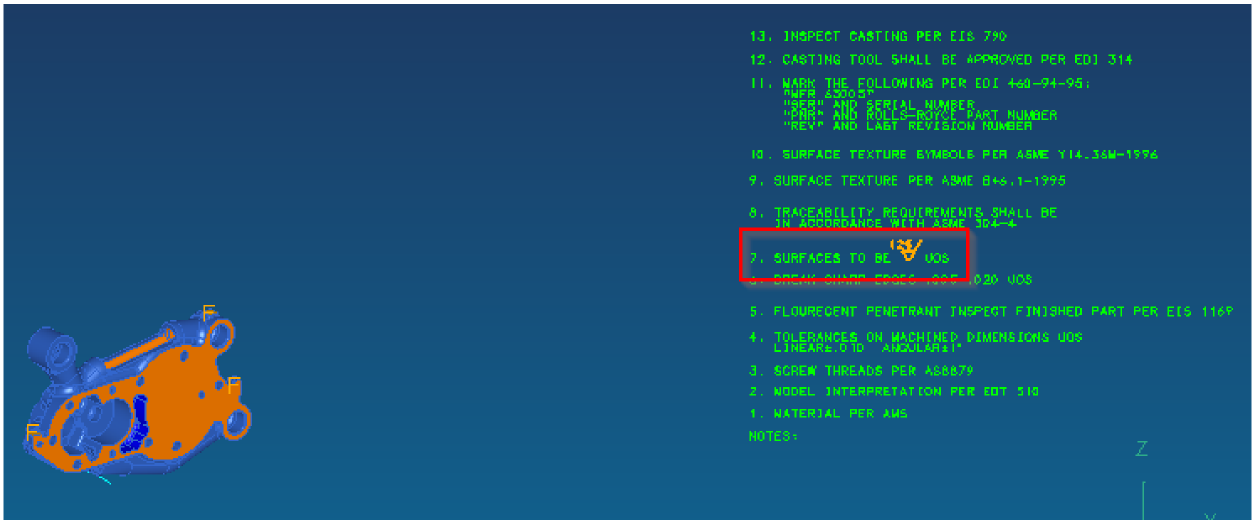
    a. Derivative import and export tolerance settings (e.g. linear and angular) need to be considered and communicated to supply chain to allow for proper data sharing. This includes reporting model precision and accuracy used for MBD creation.
    b. 3MF file type for additive manufacturing will be supported in future NX software enhancement. As of NX11, 3MF was able to be directly printed to 3D printers and also translated from JT data, but was not able to be output directly as a standalone file from NX.
    c. As of NX11, NX does not support section views translating into STEP AP242. Siemens commented that “section views are a general 242 issue… but is something we [Siemens] will address.” Therefore need to consider use of section views when translating to STEP AP242. Per Y14.41, section views are not required. The PMI can displayed using 2D sections within the 3D geometry.
    d. Zeiss Calypso software processes NX Camera View names instead of Model View names, which can lead to miscommunication of definition or at least difficulty in properly relaying information. Need to ensure that naming convention between Camera and Model View names is consistent for downstream consumption.

C. Producibility (Validation of native models) lessons as noted by ITI

1. Producibility is an evaluation of the native CAD models to determine if they are properly constructed and organized so as to be complete, non-ambiguous, and to not contain any requirements which may be impossible or prohibitively expensive. A producibility analysis of the Catia bulkhead model and the NX pump housing model was performed. For both models, the geometry was complete and unambiguous.
2. There were some issues though with the PMI which could impact downstream use of the models directly or via derivatives.

a. PMI Issues - NX

A surface finish symbol was included in notes, but not associated to model geometry was found. This is appropriate for human readability, however, for downstream applications that expect semantic PMI, this information would be ignored (Figure 28).



13. INSPECT CASTING PER EIS 790
12. CASTING TOOL SHALL BE APPROVED PER EDI 314
11. MARK THE FOLLOWING PER EDI 460-94-95;
"MFR 63005"
"SER" AND SERIAL NUMBER
"PNR" AND ROLLS-ROYCE PART NUMBER
"REV" AND LAST REVISION NUMBER
10. SURFACE TEXTURE SYMBOLS PER ASME Y14.36M-1996
9. SURFACE TEXTURE PER ASME B46.1-1995
8. TRACEABILITY REQUIREMENTS SHALL BE
IN ACCORDANCE WITH ASME 304-4
7. SURFACES TO BE 125 UOS
6. BREAK SHARP EDGES .005-.020 UOS
5. FLOURESCENT PENETRANT INSPECT FINISHED PART PER EIS 1169
4. TOLERANCES ON MACHINED DIMENSIONS UOS
LINEAR±.010 ANGULAR±1°
3. SCREW THREADS PER AS8879
2. MODEL INTERPRETATION PER EDT 510
1. MATERIAL PER AMS
NOTES:

Figure 28: Housing Producibility Issue – Surface Finish PMI

Inconsistent tolerance limits, and unrealistic tolerance values were found, which would cause confusion during inspection (Figure 29).

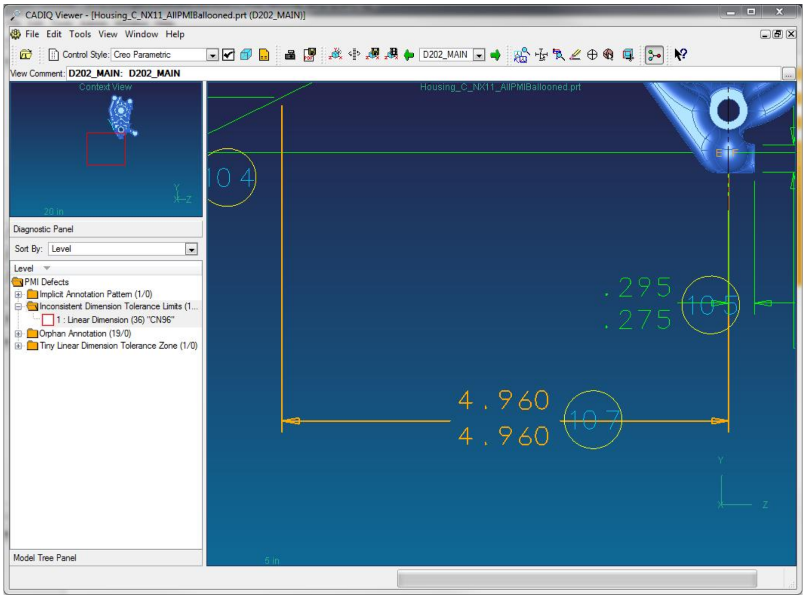


Figure 29: Housing Producibility Lesson- Tolerance PMI

Balloons are orphaned, meaning they are not attached to any model geometry. This appears to be intentional. Recommend ignoring this diagnostic (Figure 30).

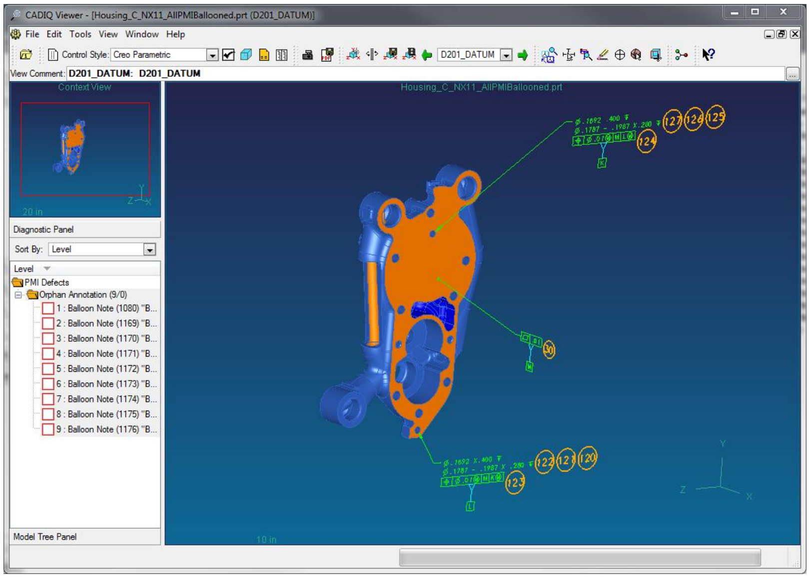


Figure 30: Housing Producibility Lesson – PMI Balloons

b. PMI Issues – CATIA

GTOL that appears to be “all around” is called out as “2 surfaces.” This would cause confusion for manual inspection, and automated inspection may include more surfaces that necessary, since the FCF is associated with all surfaces (Figure 31).

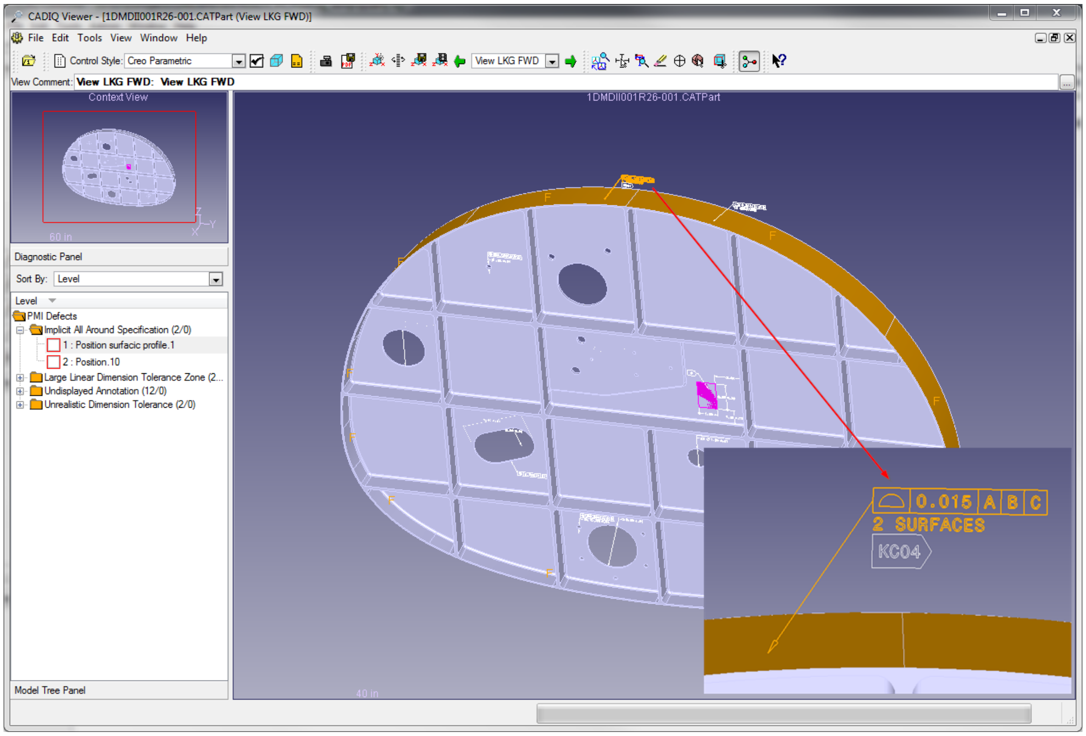


Figure31: Bulkhead Producibility Lesson - GTOL

D. Validation Lessons

1. Validation lessons as noted by Rolls-Royce

a. Validation of NX11 to STEP AP242 was noted to have issues that would lead to miscommunication of definition. If the data type (i.e. part versus assembly) is not the same in the CAD and derivative data, then inaccurate results will be provided. The pump body housing received a “clean” result when validated with CADIQ. However, it was not validating the PMI annotation because the STEP AP242 data was “seen” as an assembly and the NX11 data was seen as a part. This was a known error in how NX Model Views were processed to STEP AP242. It has since been resolved. CADIQ did not process the data properly, so a false positive was given. To further test, we performed a validation on a simple test block, with a few PMI (dimension, feature control frame, datum symbol and leader note) applied to the geometry (Figure 32).

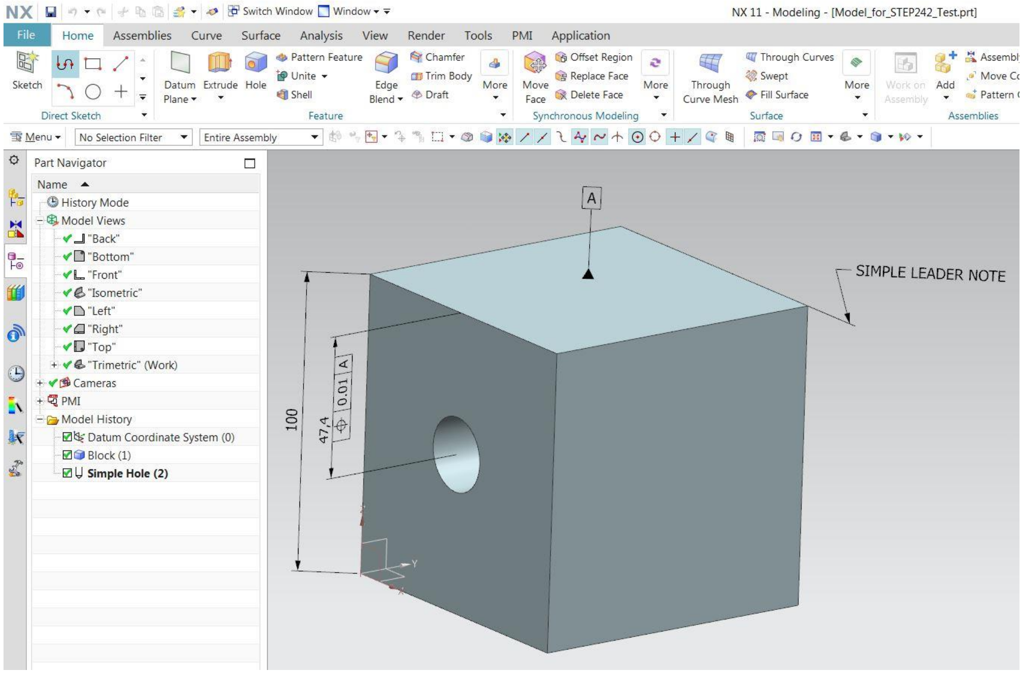


Figure 32: NX11 Test Block

When the STEP AP242 file was reimported back into NX11, the data did not translate completely (Figure 33). Note the missing feature control frame.

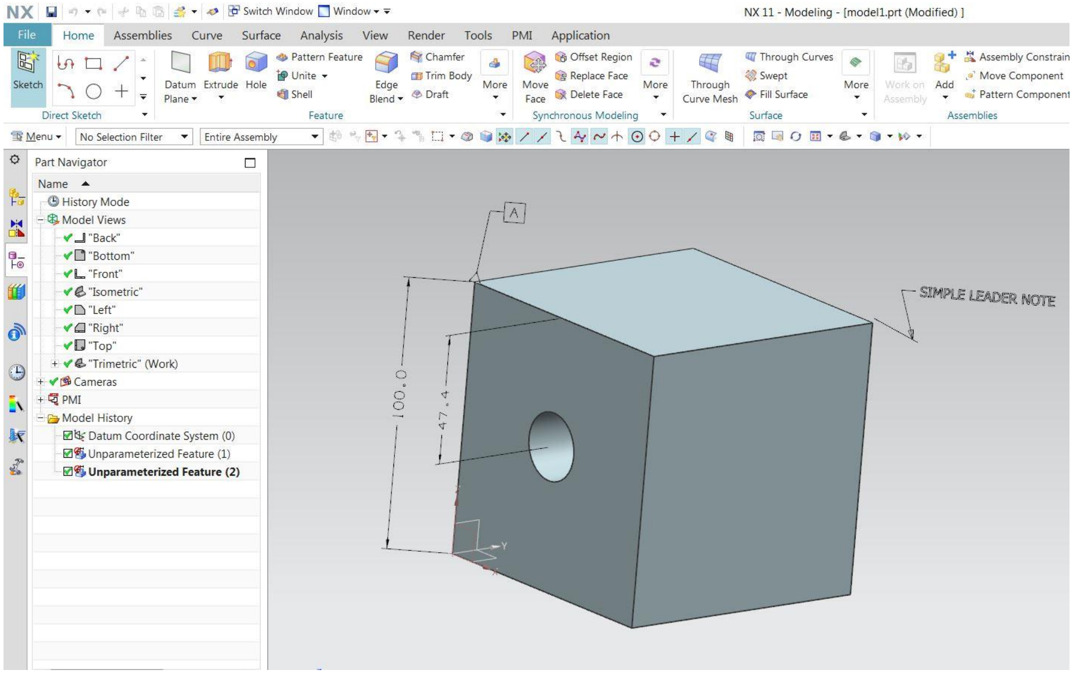


Figure 33: NX11 STEP AP242 file

When the NX11 and STEP file are validated in CADIQ, CADIQ gives no indication that there are PMI issues. Yet, when the same STEP AP242 file is reviewed in Siemens Teamcenter Visualization Mockup software (Figure 34), the PMI can be seen to be available in the file.

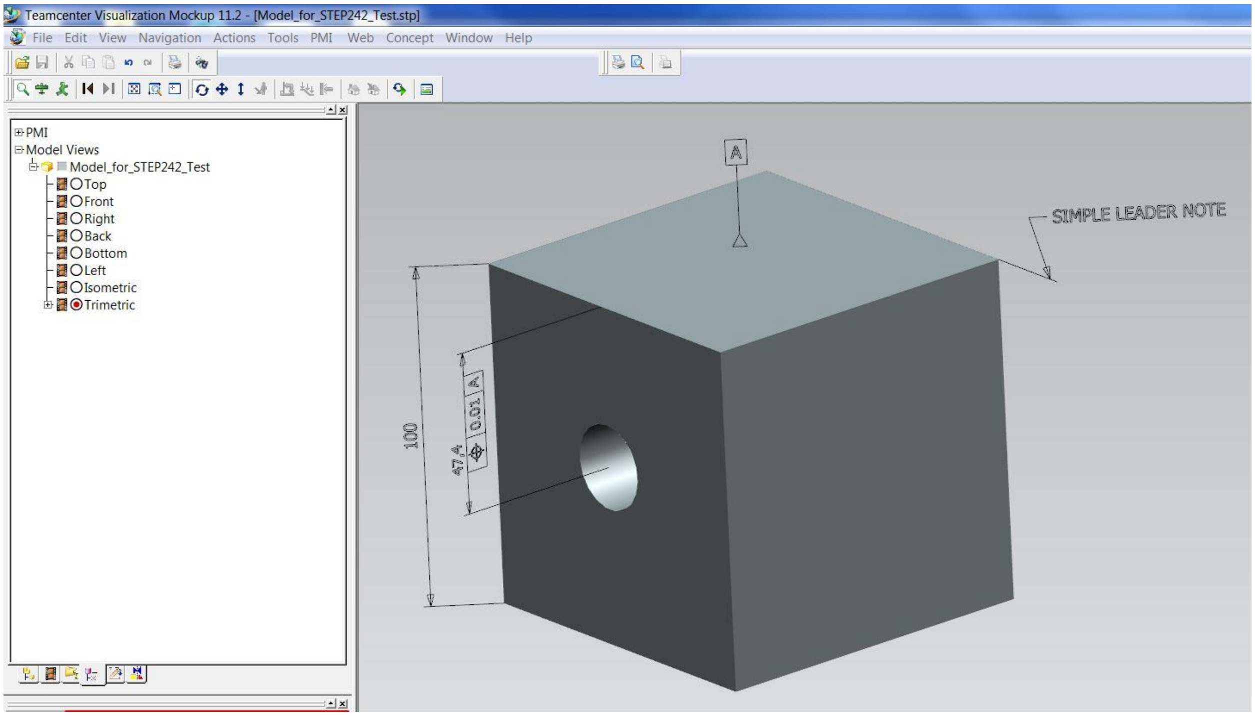
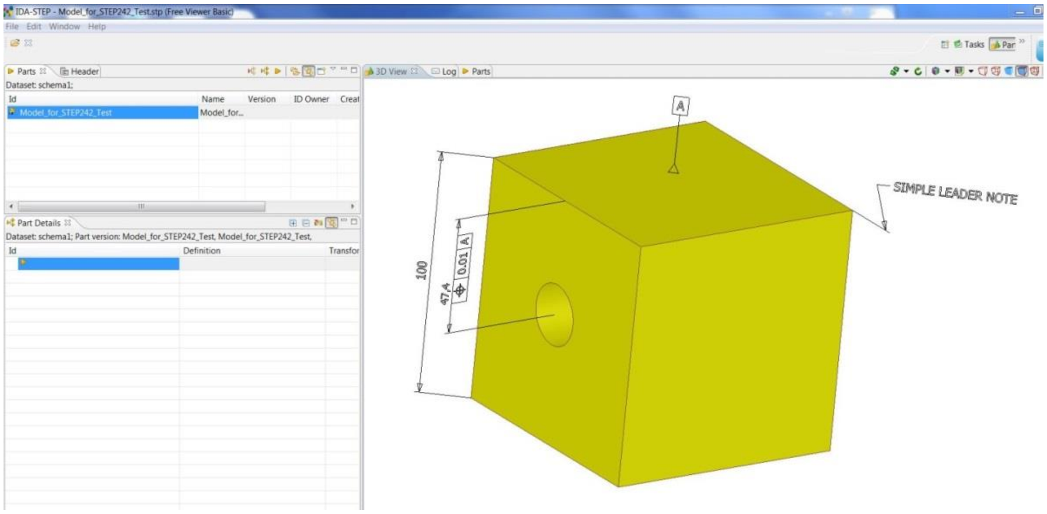


Figure 34: Test block in Mockup

Additionally, when the STEP file is reviewed in third party software IDA-STEP (Figure 35), the STEP data looks accurate when visually compared to NX11. This proves that STEP AP242 translation and validation process is still in its infancy and should be evaluated carefully as a production level utility, especially for assemblies. Software companies need to continue to develop their capabilities for translating and validating STEP AP242 data.



IDA-STEP - Model_for_STEP242_Test.stp (Free Viewer Basic)

Dataset: schema1;

Id	Name	Version	ID Owner	Creat
Model_for_STEP242_Test	Model_for...			

Dataset: schema1; Part version: Model_for_STEP242_Test, Model_for_STEP242_Test,

Figure 35: IDA-STEP view of Test block

2. Validation lessons as noted by ITI
   a. STEP 242 (from CATIA V5)
      i. Geometry Issues

         A non-solid surface was removed in the STEP file. It is not clear if this is important geometry which should be included or construction geometry which was intended to be removed. Inclusion / Exclusion of specific geometric entities or by attributes can be controlled using the Catia STEP export configuration parameters. (Figure 36).

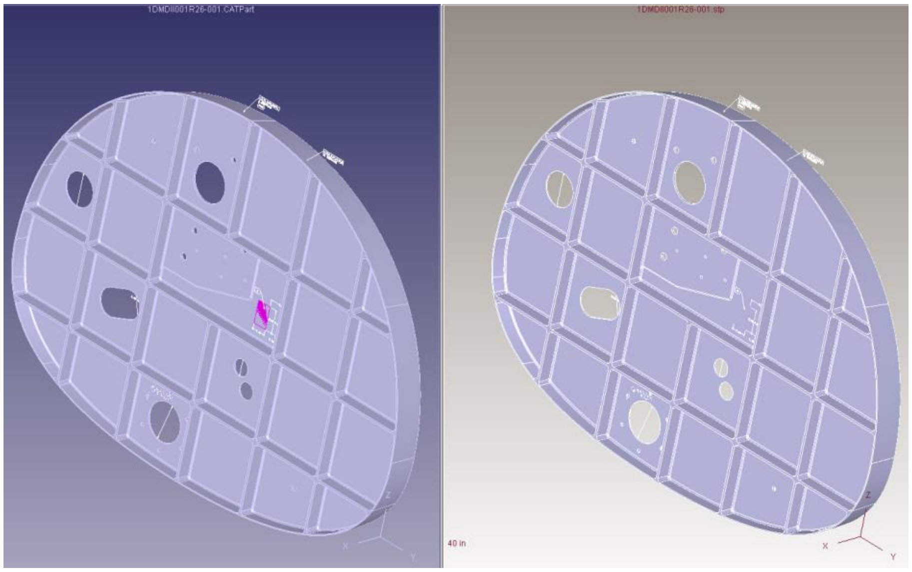
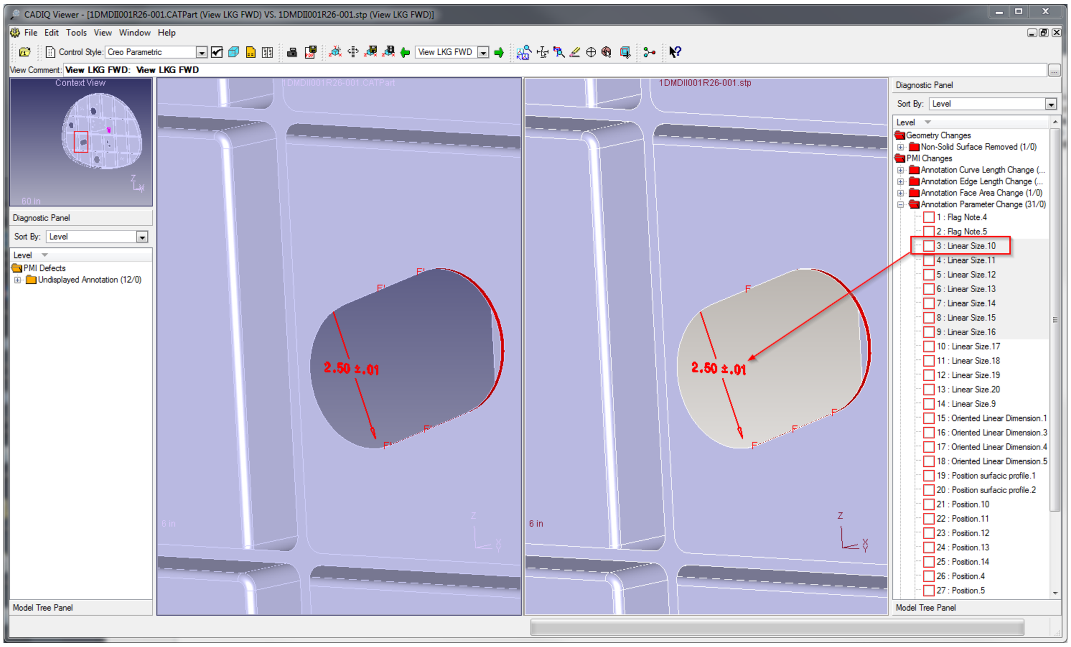


Figure 36: Bulkhead Validation Lesson - STEP242 Geometry

ii. PMI Issues

Unsupported Dimension Tolerance Format. This is a semantic property for the type of tolerance that is stored for a given dimension. It typically could be none, plus-minus, limits, etc. This has no impact for graphical evaluation, but if an application made a semantic query of the model, and searched for all dimensions with plus-minus tolerance values, it would not identify a plus-minus tolerance that had lost the property tag defining this condition (Figure 37).


CADIQ Viewer - [1DMDII001R26-001.CATPart (View LKG FWD) VS. 1DMDII001R26-001.stp (View LKG FWD)]

Control Style: Creo Parametric

View Comment: **View LKG FWD: View LKG FWD**

Diagnostic Panel

Sort By: Level

Level
- PMI Defects
  - Undisplayed Annotation (12/0)

Diagnostic Panel

Sort By: Level

Level
- Geometry Changes
  - Non-Solid Surface Removed (1/0)
- PMI Changes
  - Annotation Curve Length Change (...
  - Annotation Edge Length Change (...
  - Annotation Face Area Change (1/0)
  - Annotation Parameter Change (31/0)
    - ☐ 1 : Flag Note.4
    - ☐ 2 : Flag Note.5
    - ☐ 3 : Linear Size.10
    - ☐ 4 : Linear Size.11
    - ☐ 5 : Linear Size.12
    - ☐ 6 : Linear Size.13
    - ☐ 7 : Linear Size.14
    - ☐ 8 : Linear Size.15
    - ☐ 9 : Linear Size.16
    - ☐ 10 : Linear Size.17
    - ☐ 11 : Linear Size.18
    - ☐ 12 : Linear Size.19
    - ☐ 13 : Linear Size.20
    - ☐ 14 : Linear Size.9
    - ☐ 15 : Oriented Linear Dimension.1
    - ☐ 16 : Oriented Linear Dimension.3
    - ☐ 17 : Oriented Linear Dimension.4
    - ☐ 18 : Oriented Linear Dimension.5
    - ☐ 19 : Position surfacic profile.1
    - ☐ 20 : Position surfacic profile.2
    - ☐ 21 : Position.10
    - ☐ 22 : Position.11
    - ☐ 23 : Position.12
    - ☐ 24 : Position.13
    - ☐ 25 : Position.14
    - ☐ 26 : Position.4
    - ☐ 27 : Position.5

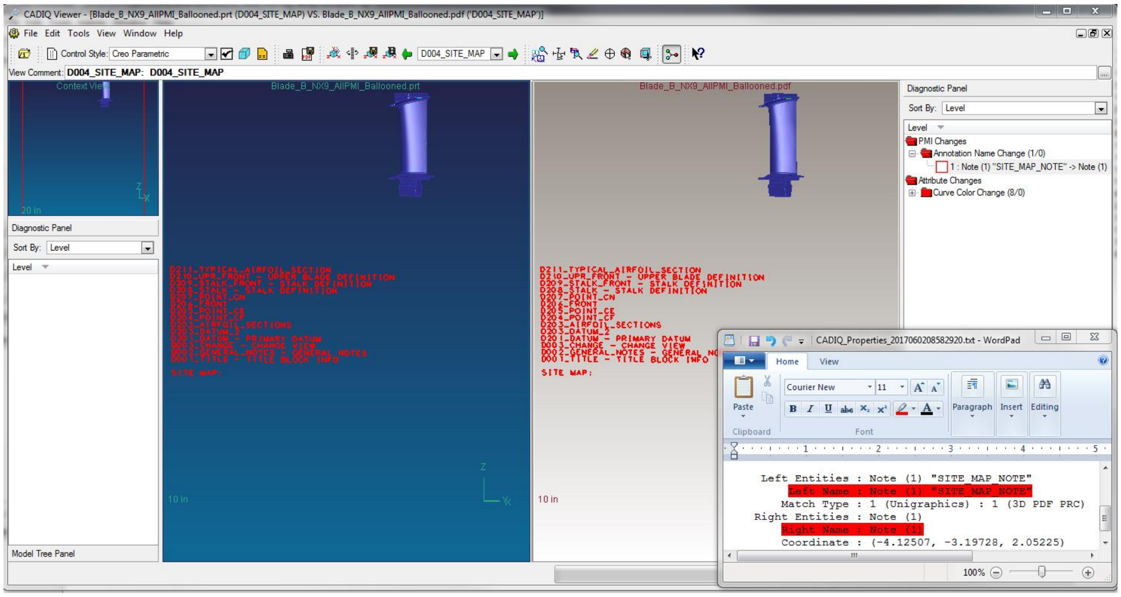
Figure 37: Bulkhead Validation Lesson - STEP242 PMI

b. PDF (from NX9)

PDF files were generated from NX9 models since, at the time of the project, Anark Core did not support PDF generation from NX 11.

i. PMI Changes

Some annotation names have changed when translating from NX to PDF. For graphical applications, this is not an issue, (Figure 38).


CADIQ Viewer - [Blade_B_NX9_AllPMI_Ballooned.prt (D004_SITE_MAP) VS. Blade_B_NX9_AllPMI_Ballooned.pdf ('D004_SITE_MAP')]

Control Style: Creo Parametric

View Comment: D004_SITE_MAP: D004_SITE_MAP

Sort By: Level

- PMI Changes
  - Annotation Name Change (1/0)
    - 1 : Note (1) "SITE_MAP_NOTE" -> Note (1)
- Attribute Changes
  - Curve Color Change (8/0)

CADIQ_Properties_2017060208582920.txt - WordPad

```
  Left Entities : Note (1) "SITE_MAP_NOTE"
      Left Name : Note (1) "SITE_MAP_NOTE"
     Match Type : 1 (Unigraphics) : 1 (3D PDF PRC)
 Right Entities : Note (1)
     Right Name : Note (1)
     Coordinate : (-4.12507, -3.19728, 2.05225)
```

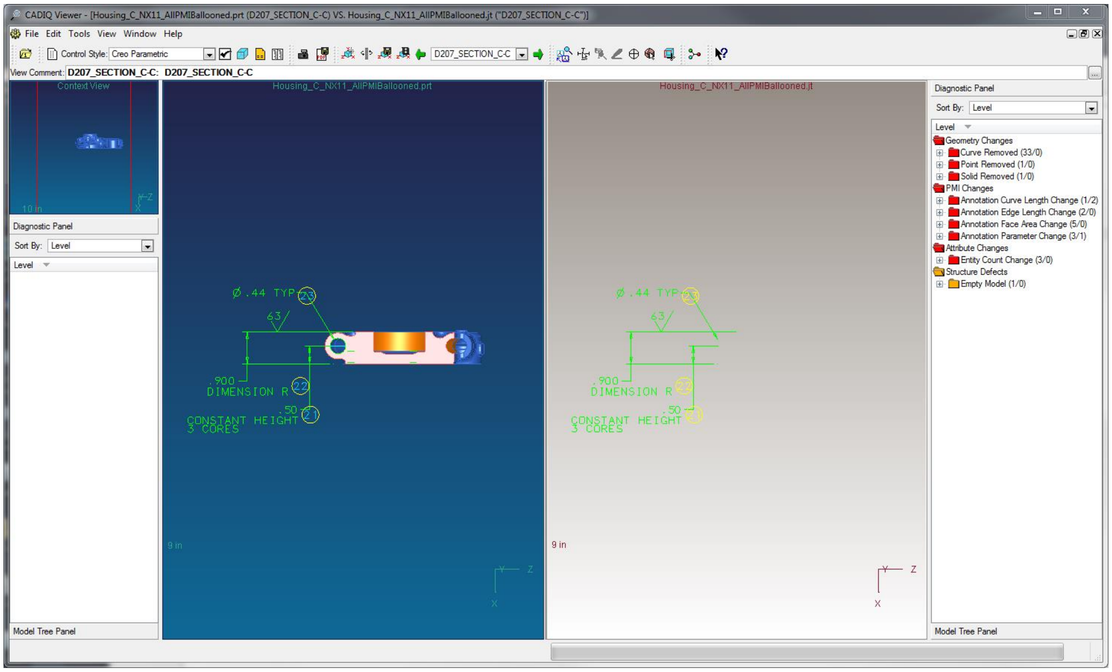
Figure 38: Blade Validation Lesson - PDF PMI

Annotation parameter changes also occurred in the translation, meaning that some annotations with associated geometry have lost some of their reference geometry. This could cause confusion in graphical use cases.

c. JT (NX11 to JT)

i. Geometry Issues

Model geometry missing from all SECTION views (Figure 39).



CADIQ Viewer - [Housing_C_NX11_AllPMIBallooned.prt (D207_SECTION_C-C) VS. Housing_C_NX11_AllPMIBallooned.jt ("D207_SECTION_C-C")]

Control Style: Creo Parametric

View Comment: D207_SECTION_C-C: D207_SECTION_C-C

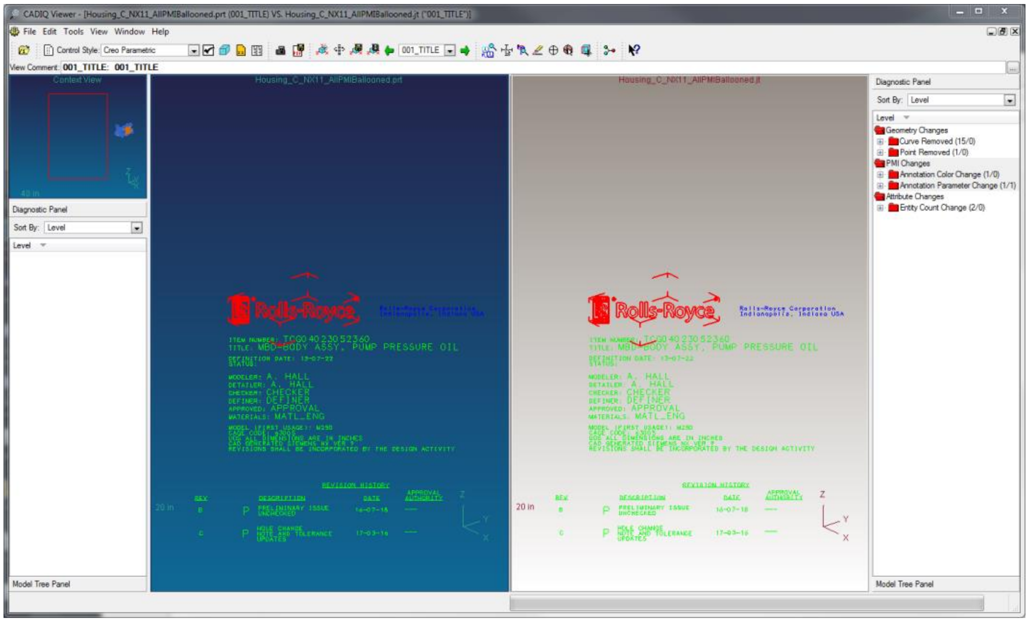
Sort By: Level

- Geometry Changes
  - Curve Removed (33/0)
  - Point Removed (1/0)
  - Solid Removed (1/0)
- PMI Changes
  - Annotation Curve Length Change (1/2)
  - Annotation Edge Length Change (2/0)
  - Annotation Face Area Change (5/0)
  - Annotation Parameter Change (3/1)
- Attribute Changes
  - Entity Count Change (3/0)
- Structure Defects
  - Empty Model (1/0)

Figure 39: Housing Validation Lesson – JT Geometry

ii. PMI Issues

RR logo has both annotation color change and parameter changes (Figure 40).


CADIQ Viewer - [Housing_C_NX11_AllPMIBallooned.prt (001_TITLE) VS. Housing_C_NX11_AllPMIBallooned.jt ("001_TITLE")]

Control Style: Creo Parametric

View Comment: 001_TITLE: 001_TITLE

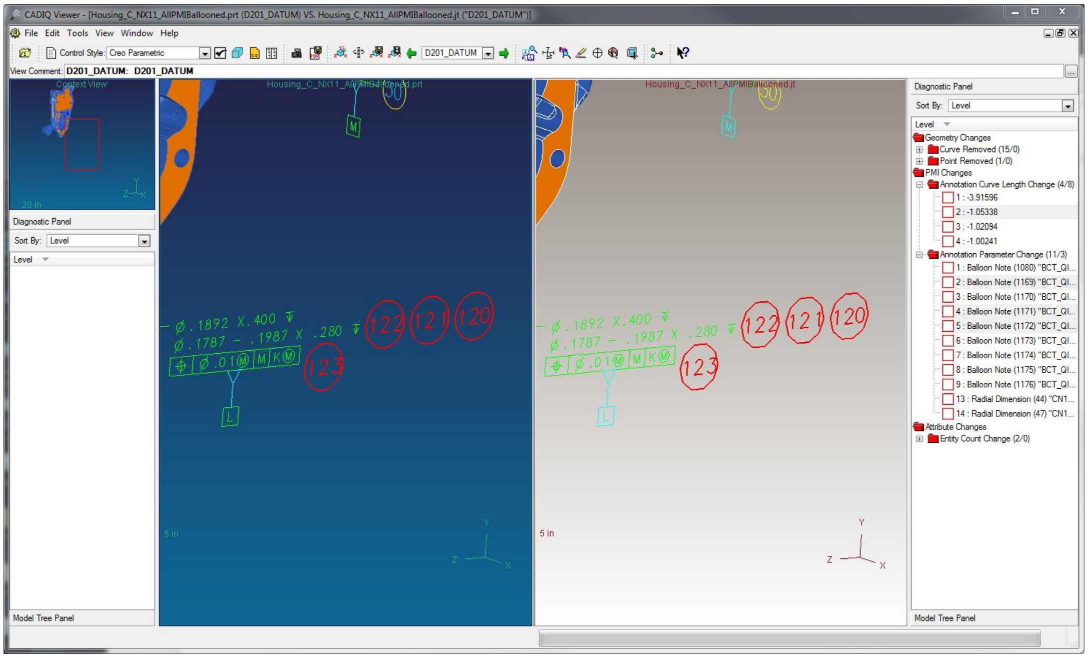
Diagnostic Panel

Sort By: Level

- Geometry Changes
  - Curve Removed (15/0)
  - Point Removed (1/0)
- PMI Changes
  - Annotation Color Change (1/0)
  - Annotation Parameter Change (1/1)
- Attribute Changes
  - Entity Count Change (2/0)

Figure 40: Housing Validation Lesson - JT PMI

Circular balloons in NX change to faceted balloons in JT. Balloon identifiers are missing from JT (Figure 41).


CADIQ Viewer - [Housing_C_NX11_AllPMIBallooned.prt (D201_DATUM) VS. Housing_C_NX11_AllPMIBallooned.jt ("D201_DATUM")]

Control Style: Creo Parametric

View Comment: D201_DATUM: D201_DATUM

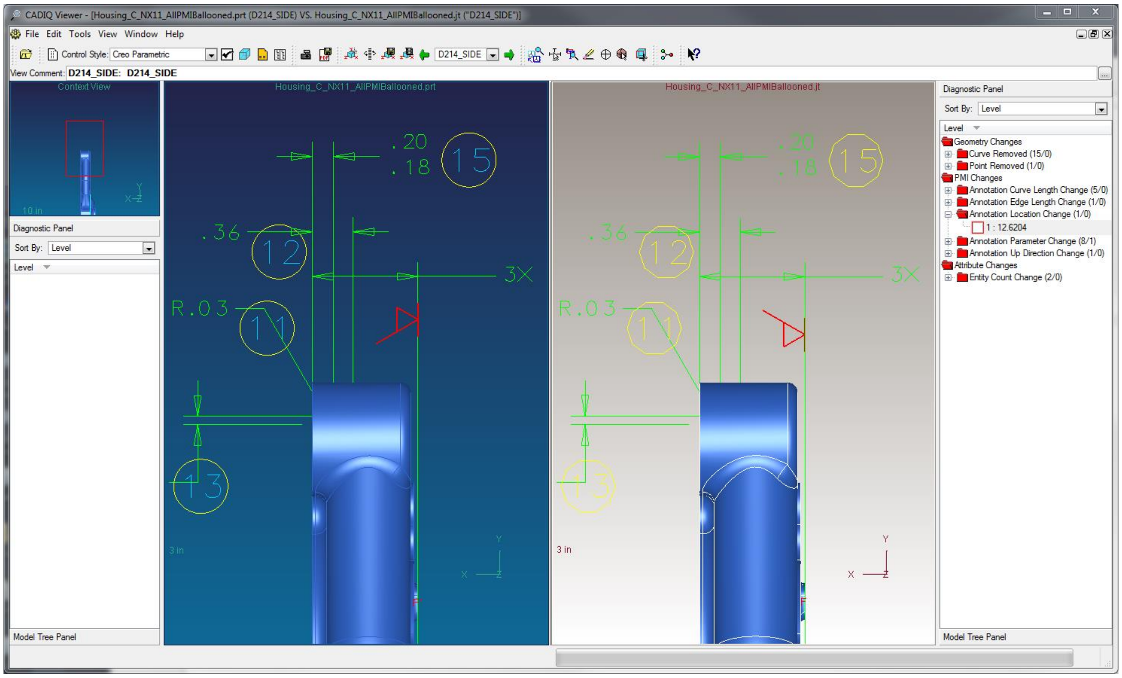
Diagnostic Panel

Sort By: Level

- Geometry Changes
  - Curve Removed (15/0)
  - Point Removed (1/0)
- PMI Changes
  - Annotation Curve Length Change (4/8)
    - 1 : -3.91596
    - 2 : -1.05338
    - 3 : -1.02094
    - 4 : -1.00241
  - Annotation Parameter Change (11/3)
    - 1 : Balloon Note (1080) "BCT_QI...
    - 2 : Balloon Note (1169) "BCT_QI...
    - 3 : Balloon Note (1170) "BCT_QI...
    - 4 : Balloon Note (1171) "BCT_QI...
    - 5 : Balloon Note (1172) "BCT_QI...
    - 6 : Balloon Note (1173) "BCT_QI...
    - 7 : Balloon Note (1174) "BCT_QI...
    - 8 : Balloon Note (1175) "BCT_QI...
    - 9 : Balloon Note (1176) "BCT_QI...
    - 13 : Radial Dimension (44) "CN1...
    - 14 : Radial Dimension (47) "CN1...
- Attribute Changes
  - Entity Count Change (2/0)

Figure 41: Housing Validation Lesson - JT PMI Balloons

Weld symbol flipped 180 degrees in JT (Figure 42).



CADIQ Viewer - [Housing_C_NX11_AllPMIBallooned.prt (D214_SIDE) VS. Housing_C_NX11_AllPMIBallooned.jt ("D214_SIDE")]

Control Style: Creo Parametric

View Comment: D214_SIDE: D214_SIDE

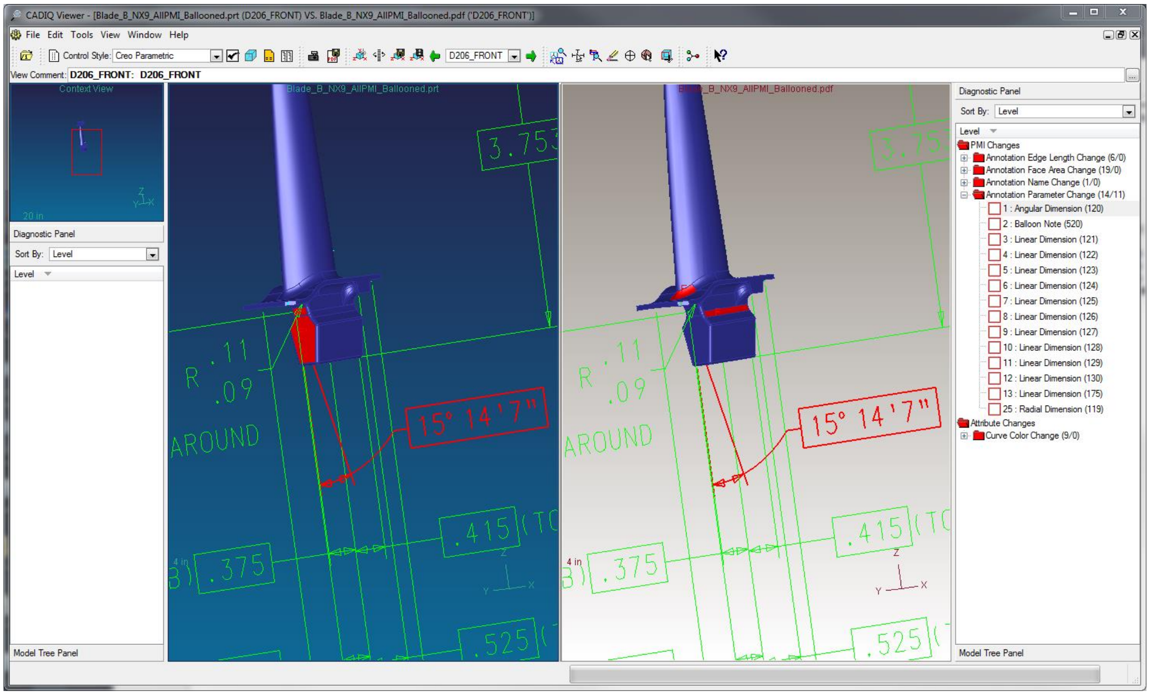
Diagnostic Panel

Sort By: Level

- Geometry Changes
  - Curve Removed (15/0)
  - Point Removed (1/0)
- PMI Changes
  - Annotation Curve Length Change (5/0)
  - Annotation Edge Length Change (1/0)
  - Annotation Location Change (1/0)
    - 1 : 12.6204
  - Annotation Parameter Change (8/1)
  - Annotation Up Direction Change (1/0)
- Attribute Changes
  - Entity Count Change (2/0)

Figure 42: Housing Validation Lesson - JT PMI Symbol

Associativity issues of some PMI in PDF (Figure 43).



CADIQ Viewer - [Blade_B_NX9_AllPMI_Ballooned.prt (D206_FRONT) VS. Blade_B_NX9_AllPMI_Ballooned.pdf ('D206_FRONT')]

Control Style: Creo Parametric

View Comment: D206_FRONT: D206_FRONT

Diagnostic Panel

Sort By: Level

- PMI Changes
  - Annotation Edge Length Change (6/0)
  - Annotation Face Area Change (19/0)
  - Annotation Name Change (1/0)
  - Annotation Parameter Change (14/11)
    - 1 : Angular Dimension (120)
    - 2 : Balloon Note (520)
    - 3 : Linear Dimension (121)
    - 4 : Linear Dimension (122)
    - 5 : Linear Dimension (123)
    - 6 : Linear Dimension (124)
    - 7 : Linear Dimension (125)
    - 8 : Linear Dimension (126)
    - 9 : Linear Dimension (127)
    - 10 : Linear Dimension (128)
    - 11 : Linear Dimension (129)
    - 12 : Linear Dimension (130)
    - 13 : Linear Dimension (175)
    - 25 : Radial Dimension (119)
- Attribute Changes
  - Curve Color Change (9/0)

Figure 43: Blade Validation Lesson - PDF PMI

E. Consumption Lessons

1. Consumption lessons as noted by Lockheed Martin

One issue we encountered with the implementation of this technology was workforce resistance. As is common with many proposed automation projects, the shop floor workforce raises the concern that the automation will reduce or eliminate jobs. While the automation would simplify the Linear Rotation & Angular (LRA) file creation and transfer processes, it would not eliminate either the Manufacturing Planner or the Operator jobs, since there are still other tasks in the workflow that must be accomplished by these personnel. The automation would, however, reduce the man-hours required to complete the tube design and build process, which reduces the overall cost of the product. Automation would also reduce the potential for human error associated with potentially selecting the incorrect bending or inspection machine, or selecting the incorrect LRA file for the current tube bend job.

An ideal solution for tube processing to reduce human error and provide a more accurate quality product would be to turn to automating tube processes and systems and placing the appropriate MBD metadata to the engineering model. Implementing this on the aircraft program and finding ways to reduce cost and improving our processes will be of great benefit.

2. Consumption lessons as noted by Purdue and 3rd Dimension

The usability of 3MF files, from a software perspective, is supported by SolidWorks 2017 for both import and export. Siemens JT-to-3mf also supports the 3MF format, but is run via command prompt. Of note, the STEP AP242 file format requires SolidWorks 2017 to have the eDrawings extension to use AP242. A major drawback of the 3MF format is that it is only supported in Microsoft Windows 8 and higher. 3MF file format likely still needs some maturation before wider adoption, but it is usable in its current state. As noted by 3rd Dimension in the evaluation of 3MF data, the format is not currently suitable for metal additive manufacturing. It is designed for polymers because it includes data for color, material blends, etc. There is new software emerging that will support more 3MF file usage.

3. Consumption lessons as noted by Zeiss

a. To leverage the automation discussed with consuming PMI in inspection - only fully semantic PMI can be used.

b. The method the PMI was created in the CAD system may affect the success the inspection software has in reading it correctly. For example; PMI referencing the centerline axis of a multi-step cylinder, will result in the inspection software not knowing what cylinder to measure. The PMI should link directly to the intended cylinder.
c. To consume PMI, CALYPSO is required to import CAD models in the native format. The CAD import function is specific to the CAD systems version and the compatibility can be limited to the supported CAD version. CALYPSO 2017 supports the following CAD systems and version.
    i. Siemens NX 11.0
    ii. CATIA R5 Version 2017 – 27
    iii. SOLIDWORKS Premium 2017 x64-Edition
    iv. CREO (ProE) 3.0

d. The practice, methods and understanding of MBD and PMI is still relative new to customers, suppliers and software providers. Users need to take the time to understand the full benefits and limitations, in their specific environment.

F. Training tutorial lessons as noted by Purdue

The tutorial was originally set to be software agnostic. This was to reduce any bias or slant towards any specific software. However after review, it was determined that the specific software used had a great impact on the results. Therefore, the software is listed with the version used in order to communicate the capability of the various software. A section of the tutorial was dedicated to describing each software in detail along with what it was used for in this project.

The tutorial provides a framework for the TDP contents based on the applicable Standards. The plan for the tutorial was to give an introduction to the document, list assumptions, and then definitions. Creating the proper Model Based Definition for a TDP was covered next, followed by an overview of the TDP itself.

The original outline for the tutorial changed throughout the writing process as feedback was given from company professionals. Clarity was needed in certain areas such as the difference between the common vs minimum information model.

The product cycle completed by the project team is included before the tutorial's appendix. This gives a graphic explanation of the complete MBD process. The appendix was also included after feedback was received. The appendix includes large screenshots of documents referenced within the tutorial and the results of the TDP transfer process.

During the creation of the tutorial, it was realized the greatest risk would be clarity. The tutorial was developed towards someone without a TDP or MBD background. Definitions were included, along with examples throughout the document. By adopting an approach to educating those unfamiliar with MBD and the communication risk was mitigated. A pilot test was performed with the tutorial to ensure the clarity of the document was satisfactory. Our finding from testing supports that the document functions to educate model-based definition novices.

G. Standards development

Standards related to MBD and TDP are an important part of successful deployment of MBD within an organization and through supply chain. Several standards were referred to during the course of the project. ASME Y14.5 was referred to for proper PMI application, and inclusion of various dimensioning and tolerancing methods. ASME Y14.41 was referred to for creation of MBD to follow a given standardized approach. MIL-STD-31000A was referred to for MBD schema requirements. NAS-3500 was referred to for TDP organization and contents, as well as the TDP Transmittal document. Neutral format data based on standards were used for the derivative data: STEP AP203, STEP AP242, 3D PDF and HTML5.

Each of the standards are similar to software, in that they continue to improve to accommodate MBD requirements. Various consortiums and committees are established to improve the standards. Some feedback about the standards was noted.

1) As noted by Purdue

   MBD related standards (e.g. ASME Y14.41) are rather comprehensive at the moment as they are written. The issues stem from incomplete adoptions or support by the CAD authoring software tools. However, Y14.5 is a standard for drawings, whereas Y14.41 is a standard for models that tries to apply some of the same information presentations constructs used in drawings (similar to Y14.5). The standards committees need to move past simply trying to display PMI and other types of data in a model in the same way they were displayed in drawings, and move towards embracing the visualization capability of the 3D environment.

2) As noted by Lockheed Martin

   The quality and capabilities of standards are not necessarily the issue for adoption of standards. It is more of an enforcement and explicit use of translator standards by the software vendors. Each vendor selects which portion of the standards they would be interested in implementing within their products. Even though; each company/end user asks the vendors about specific capabilities but at the end the vendor decides what to develop and implement within their products. Full integration of a translator standard like STEP AP242 means that all the vendor basic elements (e.g. solids, PMI, supplemental geometry) need to identified and understood so there is a mapping to the STEP data.

As discovered by the limited use cases within the project there is still significant element mapping effort that must be done by both the CAD/CAM vendor(s) and standards committee to ensure there is complete translation of product manufacturing information and associated feature characteristics between CAD/CAM systems or as a long term archival solution.

For many years; PDES, Inc. has supported the development of open standards that allow 3D product data exchange for manufacturing and archiving. Many of the members of PDES, Inc. support the use of JT for visualization, LOng Term Archiving and Retrieval (LOTAR) for archiving, and STEP for data exchange. LOTAR and STEP developers have worked together to make sure the standards are harmonized to ensure interoperability.

PDES, Inc. is an international industry/government/university consortium accelerating the development and implementation of ISO 10303, commonly known as STEP (STandard for the Exchange of Product model data). STEP, is a key international product data technology, provides an unambiguous, computer sensible description of the physical and functional characteristics of a product throughout its life cycle.

3) As noted by ITI

STEP AP242 is a new standard and Y14.41 (and equivalent) is beginning to be adopted in CAD systems. Until CAD systems fully implement the standards and they begin to get extensive real world use, it will be hard to know if they are adequate.

4) As noted by Rolls-Royce

ASME Y14.41 has areas that still need incorporated into the standard. One of which is assembly data, which is not covered adequately to provide complete guidance. Specifically the management of Bill of Material data and PMI defining component models at the assembly level needs addressed better in standards. Attribute data (i.e. non-human readable) needs to be improved upon to facilitate more automated consumption of MBD. The standard has requirements that cannot currently be met by some CAD systems, like in the area of associativity of PMI (e.g. feature control frames and related datum symbols). So while the standard does provide a comprehensive approach to MBD data management, there are areas that need developed and other areas that need to be re-evaluated for necessity of requirement.

5) As noted by Anark

> PDF is a widely adopted international standard (ISO-32000) for electronic documents. The ISO-32000-2 version of PDF includes robust support for complex 3D data through incorporation of the PRC international standard (ISO 14739). This enables PDF documents to include 3D geometry, product structure, attributes and product manufacturing information (PMI) required to support Digital Thread and Model-based Enterprise use case requirements within the manufacturing industry. PDF documents that include this type of complex 3D data are often referred to as "3D PDFs", but they are officially PDF documents. The freely available and ubiquitously distributed PDF Reader from Adobe fully supports 3D PDF content. The main short comings of 3D PDF and the Adobe Reader are a) lack of support for mobile operating systems, b) constrained options for building 3D-centric user interface controls c) No ability to extend the 3D rendering capabilities of the Adobe Reader, d) difficulty in connecting static 3D PDF content to dynamic data stored in enterprise systems such as ERP or MES, e) difficulty in customizing print output for 3D PDF documents that include 3D content with multiple MBD views.
>
> HTML5 is a widely adopted international standard, published by the World Wide Web Consortium (W3C). It is the fifth and current major version of the standard and is supported by all modern web browsers on all modern operating system platforms including desktop and mobile. Much like 3D PDF, HTML5 enables incorporation of complex 3D data within an interactive electronic document to support Digital Thread and Model-based Enterprise use case requirements for the manufacturing sector. HTML5 addresses all of the shortcomings of 3D PDF noted above.

VI. Impact of Emerging Technology

The impact of MBD and MBE can be seen within industry, even though many companies are slowly adopting MBD processes into their business. As software vendors (i.e. CAD, inspection, manufacturing, etc.) continue to improve their support of MBD, more companies will adopt MBE/MBD methods in addition to or, in some cases, in place of 2D methods. From the perspective of universities, they will need to further develop training to be used by industry

A. Impact from perspective of Rolls-Royce

Supply chain has demonstrated limited MBE/MBD maturity for full downstream consumption, without the need for human interpretation. Many companies are unable to process the MBD data with their current software. This will require significant investment to stay competitive with those companies that are already able to consume MBD data.

Linking all relevant information to the design master along with the massive amounts of related data is critical for full product lifecycle consumption. This will require continued improvement in software capability. It is not only product definition requirements, but all related data for manufacturing, inspection, service, repair, overhaul, etc.

Software companies need to adopt and support standards organization (ISO, ASME, etc.) in a timelier manner. For example, they need to comply with Y14.41 and similar standards. As well as, many standards will need to go beyond a 2D approach to definition and broaden into 3D MBD/MBE.

B. Impact from perspective of Lockheed Martin

Stronger commitment from major CAD vendors is needed to support the interoperability through standards in order to enable the Digital Thread/Digital Tapestry.

There is a lack of industry standard for assembly level PMI through ASME and ISO. This makes communicating assembly requirements challenging, compared to single component MBD.

C. Impact from perspective of ITI

MBD/MBE is in its infancy. This complex technology was envisioned several years ago and promoted by the DOD and NIST. The intent is to allow a much more automatic and seamless use of CAD data (including annotation) across the various engineering and manufacturing activities required to produce a product.

Several technologies critical to this end goal have been evolving:

- CAD model support for PMI
- The various CAD vendors have generally provided PMI support within their modeling systems. There may still be some gaps but generally these are robust.
- PMI Modeling standards.
- Adding all the PMI information that has historically been included in drawings into 3D models can result in an unusable mess – commonly referenced as a “furball” of annotation.
- In order for PMI information to be readable by humans and properly interpreted by other applications, it is essential that a common structure be utilized. (e.g. MIL-STD-31000A) Through efforts of NIST and various standards bodies, there are standards which define associativity and structural requirements.

- The DEXcenter Producibility functions utilize CADIQ to verify that appropriate PMI modeling standards are being followed to ensure downstream applications consume the information as intended.
- Programmatic exchange capability.
- One of the areas of technology needing enhancement to support MBD/MBE exchange for programmatic use was the STEP exchange standard. This was needed to allow other CAD systems and downstream manufacturing applications to realize MBD capability across different applications. As a result, a new step AP (AP242) was proposed and has gone through ISO approval over the past few years. The standard initially covered the most common types of PMI but continues to evolve to be more complete.
- The biggest issue though is the CAD and manufacturing vendors supporting STEP AP242 with semantic PMI capability. Most CAD vendors started providing some capability to support graphic PMI quickly. Graphical PMI support was also provided in AP203 and AP214 later editions. Graphic PMI allows for human readable consumption of PMI information in another model but does not have the associativity and intelligence to provide functional PMI entities which can be programmatically analyzed without ambiguity and used for further model manipulation. Semantic PMI is required for that. Semantic PMI includes the complete associativity and map to corresponding entities in the various target applications. AP242 with semantic PMI support is just becoming available now and was not sufficiently available for us to really evaluate during this project. NX 11 provided AP242 with semantic PMI support but Catia did not and the downstream manufacturing applications did not.
- Visualization support for PMI
- While STEP provides a programmatic method for exchanging MBD model information, it is basically a text file and requires a reader to visually show it.
- JT and 3D PDF formats have emerged as the leading candidates for human readable exchange. These formats are both standards and help a human understand a model.
- Validation
- CAD models are complex. In the past when drawings were utilized there was always a significant human element involved in interpreting the drawings. It has not been unusual to find errors or ambiguities in drawings which were addressed by the human interpretation.
- With MBD/MBE, the intent is to have complete 3D representations which can be used automatically throughout the design cycle. Often that involves creating derivative representations of the original CAD models. It is imperative that all derivative models accurately represent the original model. Visual inspections though are not sufficient. The complexity CAD models provide many opportunities for minor deviations in derivatives which may not be noticed visually but which could result in dramatic differences if used directly by another application.
- The ITI CADIQ application provides the more comprehensive programmatic capabilities needed to perform validation of derivative models. There are also

applications available from other software vendors which provide similar validation capabilities.
- Manufacturing application support for PMI.
- While the CAD applications themselves are moving to support PMI and semantic exchange through STEP AP242, downstream manufacturing applications have been slower at adopting this capability.

Technology is moving in the right direction but it will likely take a few more years.

D. Impact from perspective of Purdue

The market for adoption and education of Model-based Definition is large. The tutorial document created as part of this project (see attachments) provides a fundamental education to the concepts and processes of model-based definition.

The tutorial is not applicable to only aerospace or defense applications. The breadth of software covered, and the exploration of suppliers provides relevant information for all manufacturing MBD efforts. This document can support any organization looking to begin the transition towards a MBD approach to manufacturing.

Moving forward the next steps for extending training and education for MBD technical data packages will likely be industry specific guidelines for MBD adoption. Smaller manufacturers would benefit from the larger organizations researching and providing a strict guideline for adopting model-based definition. These smaller organizations may not have the infrastructure or knowledge base to make this adoption, but with proper information and guidance it is achievable and sustainable.

E. Impact from perspective of Zeiss

ZEISS views that downstream consumption of PMI in inspection as one of the most beneficial applications of MBE. ZEISS continues to invest in PMI tools to make customers successful. Calypso is currently capable of reading CAD and PMI data directly (NX, Catia, others), and significantly reducing manufacturing/inspection cost and increasing accuracy. Future plans are to read STEP AP242 as CAD vendors implement and support fully semantic PMI in the STEP AP242 models.

VII. TECH TRANSITION PLAN

This project did not develop MBD/TDP technology. The project assessed the maturity of MBD and TDP technology and capability. All the involved “tools” (i.e. software, standards and process) are already commercially available. As new “tools” were developed or became available during this project, an attempt was made to review those capabilities. Future plans for further “tool” development (e.g. Anark’s MBEWeb/HTML5 collaboration, STEP AP242 enhancements, CAD capability) will continue to improve MBD/TDP maturation in the supply chain. Any barriers for the adoption of any of the technology we reviewed (e.g. availability of software that can support STEP AP242) will continue to be removed by improvements in “tools”. Following are comments from project team.

ITI has been involved in the MBD / MBE movement since the beginning and will continue to be involved moving forward as the technology improves.

While the goal of this DMDII project was to assess capabilities of currently available technology and tools, software developers are always working on new features and products. Anark’s near term product roadmap for MBEWeb will positively impact the support for the use cases investigated in this DMDII project.

MBEWeb currently supports the following capabilities: hosting of 3D HTML5 content published from Anark Core, search, streaming of content to HTML5 clients (i.e., internet browsers). It can be sub-hosted in existing web-based applications and identity management and access control integrated with existing enterprise systems. These features support the requirements for production deployment of HTML5-based 3D TDP solution today.

3D PDF and HTML5 offer many advantages for technical data packaging vital for both large OEM’s as well as Small and Medium Manufacturing organizations (SMMs). These SMMs are a critical part of the U.S. Industrial base and the exact organizations that have the least flexibility to implement complex and expensive IT systems, standards and other means to enable supply chain communication and collaboration needs with customers and partners. Advantages of 3D PDF and HTML5 as standards-based TDPs containers include:

- Easy customization of PDF and HTML document structure and behavior for the TDP use case
- Cross-platform compatibility
- Barriers to use are low due to ubiquitous, free and easy to use Adobe Reader Software and secure web browsers

Lockheed Martin feels that there need to be stronger commitment from major PLM vendors to support the interoperability through standards in order to enable the Digital Thread/Digital Tapestry. In order to improve transition and commercialization, improved industry standards for assembly-level PMI through ASME and ISO need to be realized to remove the barriers to adoption.

VIII. WORKFORCE DEVELOPMENT

MBD/MBE reflects a new paradigm for collaboration. All parties involved need training to effectively utilize this new paradigm. That includes not only learning how to use new tools but in understanding process differences which are vital to effective utilization. Training curriculum and guidelines are a critical component to improving workforce skillset and adoption of MBD/TDP processes. This project generated a tutorial specifically for that purpose. The MBD/TDP training tutorial is based on minimum information necessary for MBD communication. The practice-based guidelines for MBD construction give a good foundation for developing extended best practices necessary for proper consumption of MBD and TDP data. The guidelines were developed for subtractive manufacturing, additive manufacturing and inspection consumption of MBD data.

Independent reviewers were asked to provide feedback on the tutorial guidance. One comment received, "After reviewing the document I obtained a fundamental understanding of model-based TDPs, despite having no prior knowledge of this information. From my viewpoint I think it is a great tutorial for someone not involved in the field, and I couldn't find or think of anything that could provide improvement to the material. I did have to re-read sections for clarification because I lack the basic terminology, but I think that's expected of an individual with no background."

IX. CONCLUSIONS & RECOMMENDATIONS

Semantic PMI can offer step change in the MBE deployment benefit in the industry, such as associativity between geometry features and attributes/external information (via hyper-linking). This allows PMI based MBE/MBD to be useful for the entire product life cycle. Its direct consumable capability could help automating downstream applications by eliminating human interpretation error and processing time. It also helps to capture valuable design/process knowledge. If the application of MBD/MBE processes stays mainly as a design discipline, it may actually inflict more investment cost until it unleashes its potential for other consumptions directly.

These advantages are HIGHLY dependent on software capability on both CAD and downstream systems. Equally important, successful MBD/MBE adoption also requires the endorsement of the design community and raising their level of knowledge of the downstream processing knowledge. A paradigm shift in itself. Continued improvements to neutral data (e.g. STEP AP242, JT, and 3D PDF) with semantic PMI will also be a critical key to success of supply chain use of MBD data. The capability offered by the neutral data is only a tool. How to use these tools is the key for success in the business. As well as the proper application of the PMI data on the MBD and transfer of data to the supply chain via the TDP.

Numerous industry standards are proven and robust under the "drawing based" practice. Their short fall comes when the design and processing intent for a 3D MBD become part of the context. Drawing-based practices rely on human interpretation.

Standards need to continue to develop in support of a MBD/MBE system. Improved standards, not only for the design aspects of design, but also the consumption by manufacturing, inspection and supply chain.

The improved software capability and standards improvements will assist the traditional "model checkers", human or software, to take into account design intent context. The traditional modeling and checking process will need to evolve to allow the supply chain to utilize the entire model for complete, accurate and reliable consumption. Unless a supply chain is able to work in one CAD system, use of the entire model will require more capable model validation tools when working between multiple CAD systems. The configurations among different CAD/PLM systems make it almost impossible to have "flawless" translation process/tool.

A common theme throughout the project is availability of CAD systems and software. During this project we were successful at identifying current capabilities that exists and found the STEP AP203 was the best option at this point in time to complete the project end to end. We had hoped some of the newer technologies emerging in the market would have been more successful but the development and implementation across the various CAD systems is still in progress. We have confidence that when STEP AP242 with semantic PMI is fully supported by various CAD systems that the results for MBD/MBE will continue to improve and increase the productivity of the workforce. With this change help lead industry to a new era of Digital Thread/Digital Tapestry with 3D models being the sole source of data and 2D Drawing being a thing of the past.

The project team will strive to support MBD/MBE capabilities into the future, including Anark's HTML collaboration tools. ITI will continue to monitor and incorporate MBE technology to assist customers in adopting MBE. ZEISS continues to invest in PMI tools to make customers successful and believe that consuming PMI downstream in inspection provides many benefits. Purdue continues to provide training on MBD and PLM for current and future workforce. As well as continued research on topics that promotes model based digital product data. Lockheed Martin would like to see a stronger commitment from major PLM vendors to support the interoperability through standards in order to enable the Digital Thread/Digital Tapestry. The lack of industry standards for assembly-level PMI through ASME and ISO impede the use of MBD. Rolls-Royce has seen supply chain demonstrate limited MBE/MBD maturity for full downstream consumption, without need for human interpretation. Linking all relevant information to the design master along with the massive amounts of related data is critical for full product lifecycle consumption. Software companies need to adopt and support standards organization (ISO, ASME, etc.) in a timelier manner.

Currently, Small-Medium Manufacturers are challenged with the adoption semantic PMI based models and the necessary software. It is an evolving process and a challenge for industry as a whole. Identifying the “low hanging fruit” by all players could help accelerate the success of the MBE technologies. Lockheed Martin’s recommendation for improved model based manufacturing is to evaluate the current product lifecycle and automate the workflows to route the appropriate released engineering files straight to the planning, to incorporate the work instructions and to feed down to the numerical control and inspection machines, reducing the need for human intervention.

Companies need to understand the MBD/TDP capabilities available in industry and within their own supply chain. This includes evaluating the abilities of various software to support the requirements needed to communicate definition information through the supply chain. Companies should adopt industry best practices for creation, translation, validation and consumption of MBD/MBE/TDP. Current capabilities (e.g. STEP AP242) are still maturing, not only as a standard, but the adoption, interpretation and implementation of capabilities within software varies across the industry.

X. APPENDICES

A. Validation & Testing Results

XI. Attachments

A. Rolls-Royce Pump Body Housing
   1. NX11 part file (CAD)
   2. STEP AP203 (derivative CAD)
   3. STEP AP242 (derivative CAD)
   4. 3D PDF
   5. JT data (neutral CAD)
   6. 3MF data (additive manufacturing derivative file)
   7. TDP Transmittal Form (Excel)
   8. First Article Inspection Report (Excel)

B. Lockheed Martin Bulkhead
   1. Catia V5R26 part file (CAD)
   2. STEP AP242 (derivative CAD)
   3. 3D PDF
   4. JT data (derivative CAD)
   5. Assembly Notes (Excel)
   6. TDP Transmittal Form (Excel)

C. Lockheed Martin Tube Project Report (Word)

D. Purdue Supply Chain MBE/TDP Improvement Tutorial (PDF)

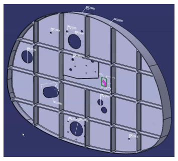
Appendix A: Validation & Testing Results

Following are the results from project activities involving translation, validation and consumption of NX 9 & 11 and Catia V5 R24 and R26 CAD data. Translations were done from CAD systems to STEP AP203, AP242, JT, 3D PDF, and 3MF for consumption.

Key for results: green cells indicate success, yellow cells indicate partial success, red cells indicate failure; X also indicates failure, ✓ indicates full or partial success. NA indicates not considered for use case. S (semantic) and NS (non-semantic) indicate the type of PMI found in the data. Asterisk(s) were used to provide further explanation of issues found.

There was several use cases ran during the project. From Level 1 OEM (Lockheed Martin) to Level 2 OEM (Rolls-Royce), using bulkhead:

TDP Transfer Process - Use Case1A (Level 1 OEM to Level 2 OEM)

	To Supplier	**Received**							
From	LM (Catia V5)								
To	RR (NX 11)		**Consumable**						
What	Bulkhead & docs		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**				
		✓	In CAD (NX11)	In Other (e.g. Adobe, TcVis)	In CAD (NX11)	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	✓	na	
What	PDF	✓	na	✓	na	NS(*)	na	✓ with errors (**)	(*) PMI was graphical only (**) Undisplayed annotation
What	STEP 242 (viewed in NX11, Vis11.2, IDA-Step)	✓	✓	✓	X (*)	X (*)	na	✓ with errors (**)	(*) no PMI or views in NX11, Vis or IDA Step (*) undisplayed annotation (all)
What	JT	✓	✓	✓	NS (*)	S (**)	na	✓	(*) PMI is "assorted parts" in NX; (**) JT Inspector: no issues
What	Catia R24	✓	✓	na	X (*)	na	na	✓ with errors (**)	(*) geometry translated; no PMI in NX11; (**) undisplayed annotation (all)
What	Catia R26	✓	X (*)	na	X (*)	na	na	✓ with errors (**)	(*) R26 not supported, only 1 point converted; (**) undisplayed annotation (all)

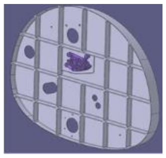
From Level 1 OEM (Lockheed Martin) to Level 2 (Rolls-Royce), using tube:

TDP Transfer Process - Use Case1B (Level 1 OEM to Level 2 OEM)

	To Supplier	**Received**							
From	LM (Catia V5)								
To	RR (NX 11)		**Consumable**						
What	Tube & docs		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**				
		✓	In CAD (NX11)	In Other (e.g. Adobe, TcVis)	In CAD (NX11)	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	✓	na	
What	PDF	X	na	na	na	na	na	na	PDF not provided
What	STEP 242 (viewed in NX11, Vis11.2, IDA-Step)	✓	✓	✓	X (*)	X (*)	na	✓ with errors (**)	(*) no PMI in NX11, Vis or IDA Step; (**) undisplayed annotation (all)
What	JT	✓	✓	✓	NS (*)	S (*)	na	✓ with errors (**)	(*) JTInspector: 50 PMI associations, 3 invalid; (**) 3 undisplayed annotation
What	Catia R24	✓	✓	na	X (*)	na	na	✓ with errors (**)	(*) no PMI in NX11; (**) undisplayed annotation (all)
What	Catia R26	✓	X (*)	na	X (*)	na	na	✓ with errors (**)	(*) R26 not supported, only 1 point converted; (**) undisplayed annotation

From Level 1 OEM (Lockheed Martin) to Level 2 OEM (Rolls-Royce), using bulkhead assembly:

TDP Transfer Process - Use Case1C (Level 1 OEM to Level 2 OEM)

	To Supplier	**Received**							
From	LM (Catia V5)								
To	RR (NX 11)		**Consumable**						
What	Asy Data (containing RR PBH STEP)		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**				
		✓	In CAD	In Other (e.g. Adobe, TcVis)	In CAD	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	✓	na	
What	PDF	X	na	na	na	na	na	na	PDF not provided
What	STEP 242 (viewed in NX11, Vis11.2, IDA-Step)	✓					na	na	
What	JT	X	na	na	na	na	na	na	JT not provided
What	Catia R24	✓	✓ partial	na	X	na	na	na	R24 catproduct failed; R24 catparts open fine in NX11, no PMI
What	Catia R26	X	na	na	na	na	na	na	na

From Level 2 OEM (Rolls-Royce) to Supplier (3rd Dimension), using pump body housing:

TDP Transfer Process - Use Case2A (Level 2 OEM to Supplier)

	To Supplier	**Received**							
From	RR (NX9)								
To	3rd Dim		**Consumable**						
What	Pump Body Housing		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**				
		✓	In CAD	In Other (e.g. Adobe, TcVis)	In CAD	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	na	na	
What	PDF	✓	X	✓	X	✓	na	✓	
What	NX9	✓	✓	na	✓ with errors	na	na	✓	Many PMI were successful; some linear dimensions were not created; "Invalid Geometry" error when generating inspection characteristics; true position characteristics failed
What	STEP AP203	✓	✓	X	✓	X	na	✓	
What	STL/3MF	X	✓	✓	X	X	na	na	none provided; 3MF not widely supported or exportable

From Level 2 OEM (Rolls-Royce) to Supplier (Zeiss), using pump body housing:

TDP Transfer Process - Use Case2B (Level 2 OEM to Supplier)

	To Supplier	**Received**							
From	RR (NX9)								
To	RR Inspection/Zeiss (Calypso)		**Consumable**						
What	Pump Body Housing		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**				
		✓	In CAD	In Other (e.g. Adobe, TcVis)	In CAD	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	na	na	
What	PDF	✓	na	✓	na	✓	na	✓	
What	NX9	✓	✓	na	✓ with errors	na	na	✓	Many PMI were successful; some linear dimensions were not created; “Invalid Geometry” error when generating inspection characteristics; true position characteristics failed
What	~~DMIS, STEP203, JT~~	X	na	na	na	na	na	na	none provided

From Level 2 OEM (Rolls-Royce) to Supplier (Purdue), using turbine disk:

TDP Transfer Process - Use Case2C (Level 2 OEM to Supplier)

	To Supplier												
From	RR (NX9 & 11)												
To	Purdue (various)	**Received**	**Consumable**										
What	Disk		**Geometry**				**PMI (S=semantic/ NS=non-semantic)**						
		✓	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	na	na	na	na	✓	na	
What	PDF	✓	na	na	na	na	na	na	na	✓	na	✓ with errors	Minor geometry issues (e.g. curves removed, surface deviation); Significant PMI differences (not translating)
What	NX9	✓	no license available for direct translation	no license available for direct translation	X	na	no license available for direct translation	no license available for direct translation	X	na	na	✓ with errors (*)	* - Minor geometry issues (e.g. small radii); Minor PMI differences (conflicting tolerances)
What	NX11	✓	no license available for direct translation	no license available for direct translation	X	na	no license available for direct translation	no license available for direct translation	X	na	na	✓ with errors (*)	* - Minor geometry issues (e.g. small radii); Minor PMI differences (conflicting tolerances)
What	STEP203	✓	X	X	X	X	X	X	X	X	na	X	No Geometry or PMI in the step file (Note; when PMI export option turned off, geometry exports)
What	STEP242	✓	✓	✓	✓	✓	X	X	X	✓ with errors (*)	na	✓ with errors (**)	(*) No PMI in CATIA V5R24, V5R26 and in Solidworks 2017; (**) STEP data seen as assembly data and not comparable to NX part data
What	JT	✓	JT not supported	JT not supported	JT not supported	✓	JT not supported	JT not supported	JT not supported	✓	na	✓ with errors	Minor geometry changes (e.g. irrelevant curves removed); Minor PMI differences (duplicate datums)

From Level 2 OEM (Rolls-Royce) to Supplier (Purdue), using electric generator:

TDP Transfer Process - Use Case2D (Level 2 OEM to Supplier)

	To Supplier	**Received**											
From	RR (NX9 & 11)												
To	Purdue (various)		**Consumable**										
What	Generator		**Geometry**				**PMI (S=semantic/ NS=non-semantic)**						
		✓	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	**Other (docs, comms)**	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	na	na	na	na	✓	na	
What	PDF	✓	na	na	na	✓	na	na	na	✓	na	✓ with errors (**)	Minor geometry issues (e.g. irrelevant curves removed); Significant PMI differences
What	NX9	✓	no license available for direct translation	no license available for direct translation	✓	na	no license available for direct translation	no license available for direct translation	X	na	na	✓ with errors (*)	* - Minor geometry issues (e.g. small radii); Significant PMI differences (unviewed annotation)
What	NX11	✓	no license available for direct translation	no license available for direct translation	X	na	no license available for direct translation	no license available for direct translation	X	na	na	✓ with errors (*)	* - Minor geometry issues (e.g. small radii); Significant PMI differences (unviewed annotation)
What	STEP203	✓	✓	✓	✓	✓	✓	✓	X	✓ with errors (*)	na	✓ with errors (**)	* - No PMI in Solidworks 2017 ** - significant geometry issues (body not translated) and PMI missing in STEP
What	STEP242	✓	✓	✓	✓	✓	✓	✓	X	✓ with errors (*)	na	✓ with errors (**)	(*) No PMI in Solidworks 2017; (**) STEP data seen as assembly data and not comparable to NX part data
What	JT	✓	JT not supported	JT not supported	JT not supported	✓	JT not supported	JT not supported	JT not supported	✓	na	✓ with errors (**)	** - Minor geometry changes (e.g. irrelevant curves removed); Significant PMI differences

From Level 2 OEM (Rolls-Royce) to Supplier (Purdue), using turbine blade;

TDP Transfer Process - Use Case2E (Level 2 OEM to Supplier)

	To Supplier												
From	RR (NX9 & 11)	Received											
To	Purdue (various)		Consumable										
What	Blade		Geometry				PMI (S=semantic/ NS=non-semantic)						
		✓	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	In CAD - CATIA V5R24	In CAD - CATIA V5R26	In CAD - Solidworks 2017	In Other (e.g. Adobe, TcVis)	Other (docs, comms)	CADIQ Validation/ Producibility	Issues
		✓	na	na	na	na	na	na	na	na	✓	na	
What	PDF	✓	na	na	no license	✓	na	na	no license	✓	na	✓ with errors	Minor geometry changes (e.g. irrelevant curves removed); Significant PMI differences
What	NX9	✓	no license	no license available for direct translation	✓ with errors	na	no license	no license available for direct translation	X*	na	na	✓ with errors (**)	* - Solidworks gaining geometric surfaces ** - Minor geometry issues (curvature); Significant PMI differences (undisplayed annotation)
What	NX11	✓	no license	no license available for direct translation	X	na	no license	no license available for direct translation	X*	na	na	✓ with errors (**)	geometric surfaces ** - Minor geometry issues (curvature); Significant PMI differences (undisplayed annotation)
What	STEP203	✓	✓ with errors (*)	✓ with errors (*)	✓ with errors (*)	✓ with errors (*)	✓	✓	X	✓ with errors (*)	na	✓ with errors (**)	* - Catia & IDA-STEP Gaining geometric surfaces ** - Minor geometry changes (e.g. irrelevant curves removed); Significant PMI differences
What	STEP242	✓	✓ with errors (*)	✓ with errors (*)	X	✓ with errors	X	X	X	✓ with errors (*)	na	✓ with errors (**)	(*) Catia & IDA-STEP Gaining geometric surfaces. No PMI imported from AP242; (**) STEP data seen as assembly data and not comparable to NX part data
What	JT	✓	na	na	na	✓ with errors (*)	na	na	na	✓ with errors (*)	na	✓ with errors (**)	* - JT2GO gaining geometric surfaces ** - Minor geometry changes (e.g. irrelevant curves removed); Significant PMI differences

From Level 2 OEM (Rolls-Royce) to Level 1 OEM (Lockheed Martin), using pump body housing:

TDP Transfer Process - Use Case3A (Level 2 OEM to Level 1 OEM)

	To Supplier	**Received**							
From	RR (NX9 &11)								
To	LM (Catia V5)		**Consumable**						
What	Pump Body Housing		**Geometry**		**PMI (S=semantic/ NS=non-semantic)**		**Other (docs, comms)**		
		✓	In CAD	In Other (e.g. Adobe, TcVis)	In CAD	In Other (e.g. Adobe, TcVis)	na	**CADIQ Validation/ Producibility**	**Issues**
		✓	na	na	na	na	na	✓	
What	PDF	✓	na	✓	na	✓	na	✓	
What	STEP 203	✓	✓	na	✓	X	na	✓	Semantic PMI does not transfer; issues with solid geometry
What	STEP 242	✓	✓	na	✓	X	na	✓	Semantic PMI does not transfer
What	JT	✓	na	✓	na	✓	na	✓	