MxD Final Report Project 15-11-08

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1. EXECUTIVE SUMMARY

Computer-Aided Design (CAD) software used to design mechanical parts continues to evolve and Product Lifecycle Management (PLM) processes continue to advance, but the transfer of data between stakeholders in the product's lifecycle has changed very little in the last 15 years. Current Model-Based Definition (MBD) is geometry centric, typically containing Geometric Dimensioning & Tolerancing (GD&T), annotations, Bill of Material (BOM) and limited processing information stored as Product and Manufacturing Information (PMI). Build data today is comprised of a combination of electronic and paper documents spread across many files and multiple formats, (i.e. PDF, HPGL, JPEG, STEP, IGES, ASCII, QIF, MatML). This assortment of delivery formats is unintelligently linked, making data transfer and more importantly design intent difficult to communicate and interpret. As a result, today's manufacturers must review, translate/interpret and/or re-enter the design data, causing their manufacturing processes to be labor-intensive and prone to error. In addition to the re-creation of the design data, significant amounts of sustainment data captured during the product lifecycle remains disengaged from both design and manufacturing. This full range of life cycle data can include material properties; design methods; analysis; manufacturing; measurement; inspection; certification test; field service; operations; maintenance; repair and overhaul data. This data is lacking meaningful connectivity to the digital thread, and access to this data is cumbersome at best. The reasons include both the complexity of the data models within which the data must be stored, and the absolute volume of new data, which is fast approaching petabytes per year.

The Model-Based Feature Information Network (MFIN) addresses the need for multiple data and file formats, configurations, and reduces or eliminates the resulting error-prone manual intervention required today. The technology innovation is required to move the MBD past geometry and 3D annotations to include items such as manufacturing planning, logical and functional behavior, and performance requirements. Leveraging this data in downstream processes will facilitate the automation of manufacturing planning and data retrieval and begin to remove the human-in-the-loop from dull, error-prone activities that detract from their more valuable work. As additional important manufacturing and sustainment information is associated with the MBD, we addressed the need for a comprehensive framework that will help facilitate standard methods of indexing, cataloging, storing, searching and retrieving the relevant information as it is required across the product life cycle. This required innovation on many fronts including geometric representations, taxonomies and ontologies, metadata in the form of preservation descriptive information, data translation and certification, information schema, and storage media. Although this project will focus on the digital thread from design to manufacturing to sustainment with a feedback loop back to design, the ultimate goal is a complete digital thread through the lifecycle.

This project includes a framework that allows the creation of links between a CAD model at the model or feature level to related data elements. This linking in large manufacturing, maintenance, and operations data sets will reduce the difficulty of locating relevant information to support phases within the lifecycle. The key innovation of the linkage will be at the feature level in addition to the part level. When this framework is implemented, seamless digital data transfer between design, manufacturing, and sustainment will be realized, and error-prone manual transcription, translation, and human interpretation of data files will be greatly reduced.

The project demonstrates to MxD industry members how an expanded MBD can facilitate a complete digital thread using a neutral framework for semantic Product and Manufacturing Information (PMI) and MFIN links. The developed MFIN architecture and the associated software tool capability will be shared with the MxD community to facilitate extending the MBD.

The resulting gap analysis will be valuable in setting the path forward. The technology and methodology developed will be available to the general public in 2020. Commercialization may be through incorporation into existing commercial tools used on the project, through the release of MFIN software extensions through MxD, or sold through the software providers. The opportunity to significantly improve and streamline manufacturing processes through the extension of the MBD fuels the team's desire to collaborate to achieve the goal of a true digital factory and enable the United States' manufacturing sector to reap the benefits of a more efficient, lower cost-manufacturing.

2. PROJECT DELIVERABLES

The following list includes all deliverables created through this project. These deliverables will be referenced throughout this final report and can be accessed on the MxD membership portal in accordance with the rights defined in the Membership Agreement.

	Deliverable Name	Description	Deliverable Type
1	Final Report	Document that provides an overview of the work that was completed as part of the project.	MS Word document
2	Implementation Guide	Document that will provide guidance on what is needed to deploy this technology, how to best use it and how can it be adapted for extended capabilities.	MS Word document
3	Workflow User Guides	Document to clearly communicate how MFIN can apply directly to the roles of various users in the engineering lifecycle. These guides will provide clarity into how specific users (mechanical designers, stress analysts, quality engineers, etc.) can utilize MFIN and what specific value	User guide (PDF or web-based) divided into sections for each workflow

		(minimization of redundant work, increased access to valuable data, etc.). The purpose of these guides is to garner support from the stakeholders within the organizations to help drive the adoption of MFIN.	
4	Software Deliverables (MFIN Code)	Files required to set up and "install" the MFIN code and schema as well as example files.	Software code
5	Video Demonstrations	Videos that allow stakeholders (end-users and decision-makers) to visualize the outcomes of the project. These videos will provide an effective way of communicating the results in an easy-to-understand format to communicate the outcomes, scale the understanding to higher-levels of the organization, and develop champions for implementing the technology.	Multiple, short videos

3. PROJECT REVIEW

Problem Statements

The following problem statements were used to identify typical use cases in product lifecycle phases that data will progress through. These represented business areas in which data was used and how the targeted process would need to interact with the data.

Problem Statements:

- Design data typically consists of multiple file types spread across disparate systems. The data in these documents are used to support downstream manufacturing and inspection processes but they are unintelligently linked to the design, making data transfer and more importantly design intent difficult to communicate and interpret.

- Independent data objects can easily become disconnected from the data source requiring manual location, interpretation, and processing of the object information.
- Steps that require a “human in the loop” are error-prone and can result in increased production costs and time.

Table 1 below lists the activities of a product’s lifecycle that were focused on in this project, their purpose and the software or data format that data is stored in.

Task	Purpose	Format
Analysis	Material Properties	MatML (export from GRANTA MI or MaterialCenter)
		Comma Separated Value (.csv)
		MSC Nastran (.bdf, .h5), HTML report, Summary data (.json)
	Analysis Results	MSC Nastran
Procurement	Acquiring Materials	CAD Model Material Properties
		Numeric Quantity
Manufacturing	CNC Machining	STEP
		IGES
Inspection	Quality	Quality Information Framework (.qif)
	CMM Program	PC-DMIS (.DMI)
		Calypso
	Inspection Plan	Microsoft Excel (.xslx)
Assembly	Bill of Materials	Microsoft Excel (.xslx)
	Assembly Instructions	Adobe PDF (.pdf)
		Image (.jpg, .png, .tiff or similar)
Maintenance & Repair	Service Investigation	Adobe PDF (.pdf)
		Image (.jpg, .png, .tiff or similar)
		Microsoft Excel (.xslx)
		Microsoft Word (.docx)
Marketing	Product Cost	CAD Material Properties
		Manufacturing & Inspection Time
		Assembly Time
		Shipment Costs

Table 1 Activities in a product's lifecycle that MFIN project focused on

3.1 Use Cases

The following Use Cases depict typical product lifecycle phases that data will progress through. For the project, these were the workflows used to represent the business areas in which the team thought would bring the most value and demonstrate how the targeted process would need to interact with the data.

Analysis

“As a design engineer or analyst, I want to more efficiently execute Computer-Aided Analysis (CAE) activates so that I can automatically retrieve material data from a material database without manual intercession and link the results to the MFIN for downstream utilization/consumption”.

Process Planning

"As a process planner, I want to automate the generation of process planning documentation by fully leveraging relevant PMI and associated data libraries so that I can reduce the amount of manual labor and errors associated with legacy processes while linking the results back to the MFIN."

Inspection

"As a quality engineer and/or inspector, I want to automate the generation of inspection programs by leveraging the model geometry and PMI made available by the MFIN so that I can reduce programming labor and link measurement results/as-built conditions directly back to the MFIN for design optimization and/or downstream consumption."

Maintenance Repair and Overhaul

"As a sustainment engineer and/or field support specialist, I want to easily upload and access necessary lifecycle data for supporting sustainment activities via a GUI so that I can streamline efforts to fully diagnose and disposition quality defects and/or part failures experience in the field and drive design optimization efforts."

3.2 Scope & Objectives

The MFIN aimed to address the above use cases by meeting the following objectives:

- Expand MBD beyond geometry & PMI required for manufacturing and inspection
- Allow feature-level linkage between CAD model and related data to facilitate
- Automating data retrieval within the product's lifecycle
- Demonstrate to MxD industry members how a complete MBD can facilitate a complete digital thread.
    - Develop a neutral framework that extends the model-based definition for all phases of the product lifecycle
    - Transition the data used to manufacture products from multiple, disparate documents to a single, digital file containing links to all the required information to be leveraged in operations and sustainment activities
    - Substantially reduce the manual, error-prone translation and interpretation methods used today to a smart digital factory where no manual intervention is required, and bi-directional communication exists.
    - Share the developed generic MFIN methodology and the associated software tool capability with the MxD community to facilitate extending the MBD
- Educate the workforce on the benefits of manufacturing using direct input of intelligent data through reduced engineering interpretation of requirements and higher quality due to fewer human errors and ultimately, reduced manufacturing build cycle time.
- Commercialization of the technologies and methodologies developed under this project.

3.3 Technical Approach

The project was organized into six technical focus areas each culminating with a milestone. The milestones and the tasks required for their completion are outlined below. For more detailed information regarding each are refer to the Implementation Guide and User Guides.

Milestone 1: Define Metallic Part and Associated Semantic PMI

For this milestone, a 3D CAD model of a machined metallic oil pump body housing in Siemens NX 12 was obtained from Rolls-Royce. Using industry best practices material properties were associated with the geometry and semantic PMI, including process planning indicators, was authored and relationships were established.

Although the oil pump body housing was the main part used for most use cases, to demonstrate multiple material definitions linking a block part with two features was utilized and consumption of data in the analysis use case was from this part.

To enable the extension of the MBD beyond semantic PMI, MFIN links were created and embedded in the relevant part features of the design to capture data and information such as material properties, inspection results, fatigue data, and field performance data. Purdue examined potential geometric and graphics programming options for embedding these MFIN linkages into part features of the model using current functionality from CAD tools and their available Application Programming Interfaces (APIs). Potential embedding options included: XML, HyperTeX, NXOpen, digital object identifiers (DOI), the JT Toolkit, NURBS functionality, MatML and PLMXML. Parametric relationships between existing geometric ontologies, spatial information within the part, and proposed materials genealogies were created. Connections to neutral file translators on the inbound and outbound side of the CAD/CAM/CAE tools were established per the existing standards (STEP AP242, JT, QIF, 3D PDF).

Purdue collaborated with team members to define necessary geometric conversion, materials information, and boundary condition information for the part to build a stress analysis scenario tool to be used in a software such as MSC Patran and/or MSC Apex and Siemens NX. The material information which was stored in a materials database was associated to part featured using the MFIN framework and was then imported into the Finite Element Analysis (FEA) preprocessor via the MFIN link to the material properties from materials database, MSC, Ansys and Materials Data Management, Inc. Furthermore, the developed MFIN framework was extended to associate material properties to non-geometric features such as spatial locations (such as a point cloud) within the part in order to illustrate linking varying properties spatially. For this purpose, the materials database's MMPDS (Metallic Materials Properties Development and Standardization) table was included with synthetic datasets for demonstration. Purdue validated the embedded MFIN links against material libraries for storing and retrieving material properties of (a) different data types of properties (b) linking to different features within the part.

Purdue also worked with team members to define Geometric Dimensioning & Tolerancing (GD&T) on the part such that the requirements are representative of part tolerances found on similar parts in industry. ASME Y14.5-2009 was used to author the GD&T, and Y14.41 was used to locate the annotation on the 3D model. Derivative models using the STEP AP242 Ed2 and QIF 2.1 standards were created, which made the model geometry and PMI available in a standard format available to other software applications in the enterprise ensuring a software agnostic solution.

Milestone 2: Develop Analysis Tool to Read in Semantic PMI

The ability of the MFIN to access Semantic PMI for structural analysis was a key requirement of the project, and to do this Purdue collaborated with software vendors to define the format and content of geometry data, materials properties, and required associations for the part along with an API to trigger the export. This is software-agnostic and may be invoked from any analysis tool, but for the demonstration, the team used the MSC Patran Finite Element Analysis (FEA) preprocessor to import the geometry and create the property associations. Automated construction of the fully defined FEA model was beyond the project scope, but a module was created to link analysis results back to the MFIN, including raw data along with a generic HTML report with fringe plots and key result values. The fringe plot data was also saved to a text file for access from downstream tools and integration with the quality control processes.

Milestone 3: Automate the Process Planning System

Lockheed Martin provided Purdue with a mock version of their standard process planning document template for a machined metallic part and knowledge of the logic used to populate that template. The process plan included the manufacturing bill of material (MBOM) and all work instruction standard text required as a result of applicable process specifications defined in the semantic PMI.

Purdue took input parameters and contextual information and arranged it in an organized way to be more programmatically accessible by a logic algorithm.

Siemens and Purdue both demonstrated the automated generation of a process planning document leveraging the CAD models created in Milestone 1 and the new capabilities developed by Siemens PLM system, Teamcenter 11. The new capability enabled the interrogation of the MBD, extraction of the semantic PMI, parsing the PMI and applying rules relevant to each data element to auto-populate a process plan template.

Milestone 4: Automate Creation of Optimized CMM Inspection Program

Capvidia's Pundit simulation technology was utilized to demonstrate the extension of the MBD from design to part measurement through the creation of a workflow that automated the selection of available measurement equipment and the generation of a Coordinate Measurement Machine (CMM) inspection program. The QIF Resources standard was used to provide Capvidia software with a description of available CMMs and sensors enabling a down-select to the optimal CMM and sensors for a measurement task. Employing the model geometry and PMI made available in a standard format from Milestone 1, an optimized, high-level measurement plan in the form of the ANSI standard QIF Plans file, were generated. To continue the extension of the digital thread, the measurement plan must be passed to a CMM software package to convert it to a CMM inspection program, and then execute the inspection. Both Siemens NX CMM software packages were evaluated. Capvidia worked extensively with the Siemens NX APIs to implement import capability for QIF Plans files, including the creation of the CMM inspection program.

Milestone 5: Create Feedback Loop to Take Operational Data Back to Design

Under Milestone 5, a feedback loop using MFIN links to connect critical part features through a series of designated keywords mapped to existing design and manufacturing ontologies was created. Purdue and Rolls Royce collaborated to design the framework within the MBD environment. An interface was developed that includes pre-constructed queries to ensure efficient retrieval of information from within the MFIN file. For example, when users require information related to a part feature, they would select that feature ID within a CAD viewer application such as MBDVidia, view MFIN data linked to that particular feature, and retrieve the desired information. The resulting information can either be stored or consumed by a requesting program. The proposed feedback loop will take the operational data from the field back to the design.

The MFIN link relays the keywords to an app that assembles and executes a data query based upon those keywords using data that is tied back to a commercial PLM implementation as the storage and query mechanism while maintaining the connectivity to the CAD model and manufacturing planning data.

Milestone 6: Use of MFIN for LOTAR

The objective of LOTAR International is to develop, test, publish and maintain standards for long-term archiving (LTA) of digital data, such as 3D CAD and PDM data. These standards will define auditable archiving and retrieval processes. The use of the standard series by other branches of industry such as the automotive or shipbuilding industry is possible. The results are based on the ISO 14721, Open Archival Information System (OAIS) Reference Model. The documents for the standard are published as the European Norm (EN) 9300-xxx series under ASD-STAN in Europe and, in cooperation with the AIA, under the National Aerospace Standard (NAS) 9300-xxx.

On August 29, 2019, MxD 15-11 project team members met with members of the LOTAR organization to discuss how the MFIN effort relates to LOTAR requirements and guidelines. The question asked was whether the MFIN data format -- being based on the QIF ISO/DIS standard -- would be a valid approach for complying with LOTAR requirements.

LOTAR is primarily dependent on semantic MBD formats which are formalized as internationally governed standards bodies. This ensures that the data is of high fidelity, and stored using a language and grammar which are unambiguously defined. Typically, STEP AP242 is used as the mechanism for LOTAR.

Given these basic criteria established above, it seems likely that the MFIN approach could be compliant with LOTAR requirements. A mapping study carried out by NIST between QIF and STEP AP242 helped to establish that the semantic nature of QIF maps well to STEP AP242. Since STEP AP242 reaches a level of semantics adequate for LOTAR purposes, then it seems that QIF would be suitable from this perspective as well. QIF is currently an ANSI standard but is currently a Draft International Standard for ISO. It has been unanimously voted by the ISO TC184/SC4 committee to become an official ISO standard 23952. Therefore, it will soon be a recognized international standard.

Given the above, and the MFIN is a superset of QIF data, then it follows that the MFIN approach could be highly compatible with LOTAR requirements and guidelines. However, it is important to note that each organization implementing LOTAR is required to define compliant processes on their own, and not take any such statement as this as "proof" of LOTAR compliance.

Implementation

This section discusses how the team approached the implementation of the technical solution in a step by step manner.

Familiarization of Workflow

The team began by becoming familiar with the basic workflows a product will encounter throughout its lifecycle to ensure a thorough understanding of how the MFIN could be used. The workflows identified and the reasoning behind each are described below.

- An analysis workflow was identified to be important by Purdue because it is typically the first point of iteration as the design is refined. Linking the design more directly to the FE model helps speed the analysis process and eliminates a source of miscommunication.
- A Process Planning workflow was identified to be important by Lockheed because manual generation of process planning documents is time intensive and error-prone.
- An Inspection workflow was identified to be important by Capvidia because this is where the design requirements are compared against the manufactured product to ensure an adequate level of quality. GD&T is assigned to a product definition at design time with the express goal of validating the manufactured workpiece to the GD&T during the inspection process. An enormous amount of time is spent on the duplication of effort of re-entering GD&T data at this stage. Additionally, modern measurement processes gather an enormous amount of data related to production capability -- most of which is discarded and simplified to a "pass"/"fail" inspection decision. Bringing measurement into the digital thread opens enormous opportunities for more product/process data, and better decisions.
- A Maintenance, Repair and Overhaul workflow was identified to be important by Rolls-Royce because current methods to search and retrieve data to perform a service investigation are time-consuming and often incomplete. The MFIN will enable a streamlined approach to finding all data related to a product.

The reasoning behind of each of these workflows are covered in section 3.1 of this document.

Familiarization of Data Elements

From the workflows discussed above, the team then compiled a list of potential data types that might be referenced by the MFIN. The initial list of data types that were identified to include were:

Metadata in the 3D CAD Model.

Metadata would be used in the analysis workflow and could be connected to the following types of data:

- 3D Annotations and PMI
    - This type of data captures inspection information in a model-based definition.
- Text notes
    - Like notes on a drawing, notes can also contain inspection information.
- Parameters
    - Parameters can be defined to perform calculations and can be stored or read by a PDM system.

Materials information
Materials information would also be used in the analysis workflow and would require connection to MatML material properties file, extracted from a cloud-based materials database (GRANTA MI or MaterialCenter).

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External documents

- Other types of data may be required throughout a product's lifecycle. There are no restrictions of the file types but a few examples of the most common file types might includeMS Office Documents (Excel, Word, PowerPoint)STEP Files
- This file type stores CAD Geometry in a neutral format to be easily consumed by multiple CAD systems.CNC Program Files
- Use to program a machine to produce a part through a computer numerical controlled file.CMM Program Files
    - Used to allow a coordinate measuring machine to inspect a product.

Format Selection

Next, the team had to decide an optimal format to store MFIN data. Existing formats were evaluated as well as developing a new format and key points for each option are noted below.

Developing a new format
Given the timeframe of the project, this option was deemed to be not feasible in addition to the fact that industry might be reluctant to adopt yet another format that is not an official standard.

Qualify Information Framework (QIF)
QIF is an existing, free XML framework standard (ISO/DIS 23952) which defines, organizes, and associates quality information at the CAD feature level. Adopting an existing framework that is already standardized by industry would allow potential end-users of the MFIN to be confident with the integrity of the format.

The current version allows digital data to be intelligently organized and passed efficiently throughout the supply chain including: measurement plans, results, part geometry and PMI, measurement templates, resources, statistical analysis, and more. Leveraging the existing capability to include more data types would be not only simpler to implement but could add on to benefits to the QIF format if the modifications go through the standardization process.

The QIF is an XML (Extensible Markup Language) format which is a technical format that is machine-readable, but it is also easy for humans to read with only a small learning curve. XML was designed with the intent of extending structures with additional data. This aspect of QIF was one of the leading reasons that made this format a good choice.

STEP AP242 (Standard for the Exchange of Product Data)
STEP (ISO 10303) is another well-established format that has been in use since 1994 allowing communication between CAD systems through a neutral file format.

The STEP format is not “human-readable” without training and therefore was a less desirable format.

Resulting format selection

In the end, QIF was selected because the format was the most easily extendible option that was easy to use out of the box.

Content Storage

The team then determined what to store in the MFIN file, namely considering storing links to the connected data versus storing the actual data in the MFIN file. Storing links to relevant information removes the risk of redundant data in the CAD model and MFIN file. Data written in multiple locations can easily become unsynchronized. Storing links in the MFIN file also results in a smaller file size.

Swim Lanes

Swim Lanes for the use cases described in section 3.1 were then documented to layout workflow for the demonstration of the final product. Four swim lanes were identified as outlined below.

Analysis/Material

This swim lane demonstrates the use of an MFIN by the analysis process to access CAD and linked materials information. The process is initiated by a design engineer in cooperation with a materials engineer, who reviews the design and assigns a specific material ID to each feature using an interface to one of the materials databases (MaterialCenter or GRANTA MI).

After the required links are established, the structural analyst can use an identifier associated with the CAD model in the MFIN to initiate the creation of the analysis model. An interface in Patran lets the analyst enter this identifier and an address for the MFIN (a file) and initiate model creation. The process wrapped by this form will use the MFIN API to get the CAD and material information along with associations (STEP, MatML, and JSON files respectively) and use this information to create geometry with associated material properties. The process of completing the MSC Nastran FE model with mesh, loads, and boundary conditions was not automated as part of this process but could be in the future.

Once the analysis is complete the results are then passed back to the MFIN using another API call. As part of this project, a standard and generic set of data is stored, including the input file and binary results from MSC Nastran along with an automatically generated HTML report that shows fringe plot images of stress results on each feature and peak result values. To better integrate with downstream software, the data plotted in each fringe plot is also included as a text file that can be used by other software to overlay stress results with other product views—e.g. quality images in MBDVidia.

The goal of the implementation of this swim lane was not to fully automate the analysis process. Automation can be done as part of a future MFIN implementation, but that is not new—the more significant capability demonstrated here is the flow of data between the disparate software packages and the associations that enable it. This facilitates data transfer, speeds the process, and reduces the opportunity for miscommunication. The process was specifically designed to be independent of the software being used, so the interactions of the MFIN with external software is set up to be initiated from the external tool, not the other way around. This makes the system less dependent on what other software is used.

Inspection/Measurement

This swim lane demonstrates the use of an MFIN for the automated generation of a CMM plan. The process is initiated by a design engineer authoring PMI in the CAD model. The data is then exported to a QIF file that contains PMI information and links to information that was captured by the MFIN. From this information, CALYPSO and NX CMM were used to generate a CMM plan which is then used by quality engineers to inspect physical parts when they are produced. Measurement data collected from an MBD-based measurement process should be traceable back to the authority model. This traceability means that all measurement data is mapped back to the "single source of truth" – the master CAD model housed in PLM. The results are linked back to the MFIN via a script to complete the loop of information.

Process Planning

This swim lane demonstrates the use of an MFIN for the process of generating a process planning document. The process is initiated by a design engineer authoring PMI in the CAD model. The data is then exported to a QIF file that contains PMI information and links to information that were captured by the MFIN. The code is then executed to rearrange MFIN data using logic to allow for more efficient parsing of the data. This information is then taken by another set of code to populate the information into a standard process planning template.

MRO (Maintenance, Repair & Overhaul)

The ability to search and access product data throughout the lifecycle is critical for a complete investigation. Once an investigation is performed, service engineers need the ability to upload results and information against the data. The service data will then be available for other areas of business to incorporate into future design improvements. MFIN will be developed to support MRO service investigation and sustainment activities. The MFIN needs to include a Graphical User Interface (GUI) to allow easy, concise interaction with the data.

Implementation

A test environment referred to as a "sandbox" was set up at Purdue to contain all the necessary software required to develop the MFIN as shown in Figure 1.

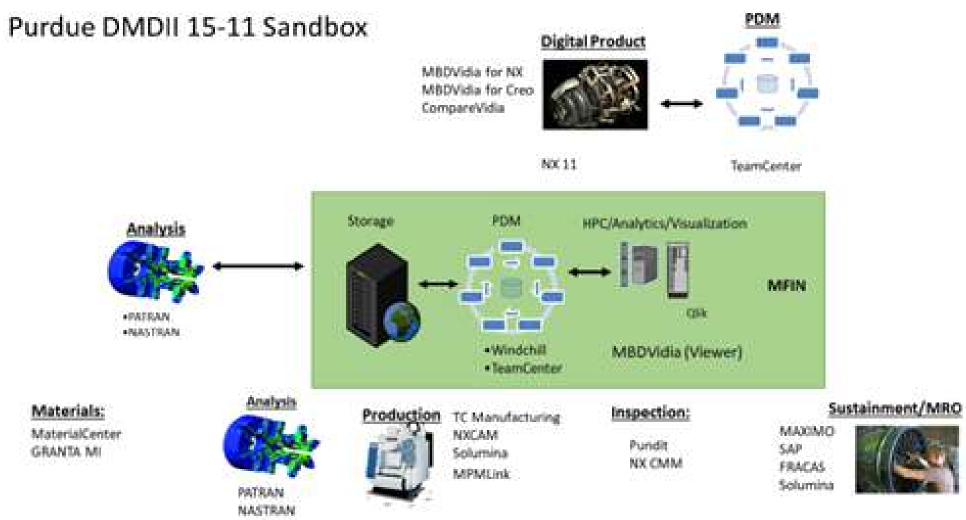

Figure 1 Graphic representing Purdue MFIN Sandbox environment.

The software used in this implementation is listed in Table 2 below. Specific license information, including add-on CAD modules, can be found in the Implementation Guide.

Vendor	Software	Purpose
Siemens	Teamcenter	Data Management
	NX	CAD Design
	NX CAM	CAD Manufacturing
MSC Software	MSC Nastran	Finite Element (FE) analysis
	Patran	FE pre/post processing
	MaterialCenter	Materials Database
Granta	MI (Material Information)	Materials Database
Capvidia	MBDVidia	Geometry Viewer?
	Pundit	Co-ordinate Measurement Machine software for generating inspection plans
Python	Python	Passing MFIN data to other software
Microsoft	C#	Passing MFIN data to other software
	C++	Passing MFIN data to other software
Digital Metrology Standards Consortium (DMSC)	QIF	Storage of MFIN information

Table 2 Software Used for MFIN Development

Selected code and scripting languages to be used on this project were installed, but the MFIN is not limited to using only those selected.

User Interface

The ability to interact with the MFIN data and navigate through the data linkages became evident as the project evolved. A concept User Interface was developed to demonstrate how MFIN data could be used and it is available as part of the package of data provided by MxD for this project, however further development would be needed to tailor the interface for company-specific needs.

Demonstration story

The team developed demonstrations to show how MFIN would integrate into the four uses cases outlined in section 3.1. These demonstrations were used to validate the developed framework as well as how the data would be accessed by an end-user. The demonstrations were also presented to higher-level management at both Lockheed and Rolls-Royce onsite meetings to get buy in to proceed with pilots of the MFIN.

3.6 Planned Benefits

The project is planned to provide the functionality to connect data used throughout a product's lifecycle to a CAD model or specific features within a CAD model. This will be accomplished by deploying the MFIN schema into pilot or limited scope activities in real business areas. The pilots will help mature the MFIN into those areas for extended use in more areas. Once more mature, the use of the MFIN as the primary data linkage method will make MFIN a key business component.

The project aims to decrease manual data retrieval, which is error-prone and time-consuming, which will result in more seamless data exchange when data moves throughout the enterprise. Seamless data exchange will eventually extend into the full supply chain. There are more key benefits listed below:

- Expands MBD beyond geometry and 3D annotations
- Single, digital dataset containing all the required design information to be leveraged in operations and sustainment activities
- Reduced interpretation error and manufacturing cycle times
- Project solution involves complete lifecycle, including feedback throughout lifecycle
- Neutral framework to be implemented by any software

4. ANTICIPATED KPI'S & METRICS

Table 3 below outlines the anticipated key performance indicators and metrics used to evaluate the success of the project outcomes in comparison to the current state and proposed goals.

Metric	Baseline	Goal	Results	Validation Method
Reduced time to generate Process Planning Documents	Manufacturing Planning will typically take 4 to 8 hours for an experienced Planner. Up to 2-3 days for a rookie.	95% Reduction	Time Span Reduction 10 minutes for Plan Generation vs 4 hours to 8 hours = 95.8% to 97.9% Respectively	Demonstration shows Process Plan Generation is less than 10 minutes.
Reduced time to locate documents required to investigate a service issue.	Service engineers typically take up to 1 week to locate all necessary documents/data to perform a full-service investigation	Reduce time by 50% to locate documents/data	In limited testing, time was reduced by 40%	Documented previous method used to locate all documents/data. Compared time to use MFIN User Interface to locate similar documents/data
Automation of CMM program generation	For manual offline CMM programming of the pump housing, the time needed is about 5 hours.	Reduce offline CMM programming time dramatically	Offline programming time reduced to 10 minutes – 97% reduction of time spent on this task	Program created manually; program created via MBD. Each work task was timed.
Optimized CMM program	No quantitative method is typically used to arrive at a CMM program with known measurement uncertainties	Provide an easy-to-use quantitative method of assessing measurement uncertainty	Pundit CMM integrated with NX CMM requiring just a click of a button. Running Pundit with the default NX CMM pump housing program allowed us to reduce measurement uncertainty by a factor of 4 (with minimal effort)	Pundit was integrated with NX CMM
Reduce time to create analysis geometry with properties, ease communication	Engineer gathers geometry and material data from disparate sources, manually imports and creates associations.	Reduce import time and association process by >90%, reduce error opportunity	Engineer enters model identifier and MFIN location, process completes automatically	Process demonstrated and timed
Reduce time to report results, standardize form, archive retrieval	Engineer saves individual plots, gathers into report with other key data, stores locally	Reduce report generation time by >90%, standardize form, centralize storage	Engineer initiates report generation, process gathers standard data set and archives with direct model connection	Process demonstrated and timed

Table 3 Anticipated Key Performance Indicators and Metrics

5. TECHNOLOGY OUTCOMES

The following sections cover the resulting technology and how the team arrived at those outcomes. For more detailed information about each section, refer to sections 3 & 4 of the Implementation Guide.

SYSTEM OVERVIEW

The MFIN is a framework that establishes connections between a CAD model or CAD model features, and other relevant information, such as material properties, analysis input and/or results, process planning documents and any documents required to perform MRO procedures. Figure 2 shows a representation of what an industry configuration might look like, including the software used for those tasks, and therefore what the MFIN could interact with.

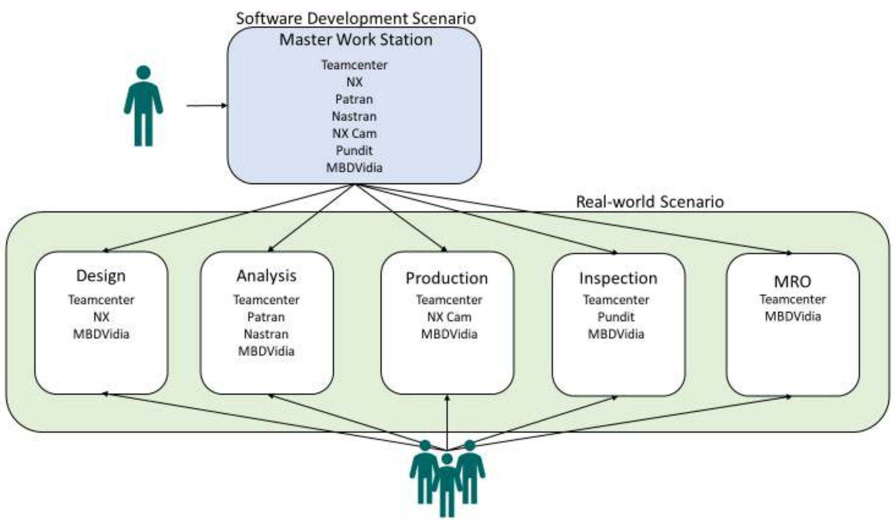

Figure 2 Graphic representation of industry configuration

Refer to Section 8 in the Implementation Guide for more detailed information regarding the system.

The MFIN schema files are extensions of the common industry standard Quality Information Framework (QIF). Two important aspects of QIF leading to this decision were: (1) it is an open MBD standard with a notion of Features, and (2) it is implemented with XML and XSDL. For these reasons, an established standard was used as a base, and the necessary extensions were made to the standard for the project. Root elements to the QIF schemas were added, such as "MFINMaterialDefinition", "MFINAnalysis", and "MROData". These elements could be added to the top level of a QIF Document to carry structured data related to Analysis and MRO workflows.

SYSTEM REQUIREMENTS

A 3D CAD system that can author 3D CAD model geometry with PMI information in it is required. In order for the MFIN to read data inside of that CAD model, a wrapper code is used to take that information and store it in an XML file. The XML file is formatted based on the QIF standard utilizing a new schema that was developed specifically for the MFIN.

To set up and utilize the specific workflows outlined in this project, additional requirements are necessary. A summary of the additional elements that were used in the development of this project are listed in **Error! Reference source not found.** in Section **Error! Reference source not found.**.

The figure below shows a basic configuration of the MFIN in red and optional elements in blue. One or more of the optional elements could be used for MFIN purposes depending on the aspects that are implemented.

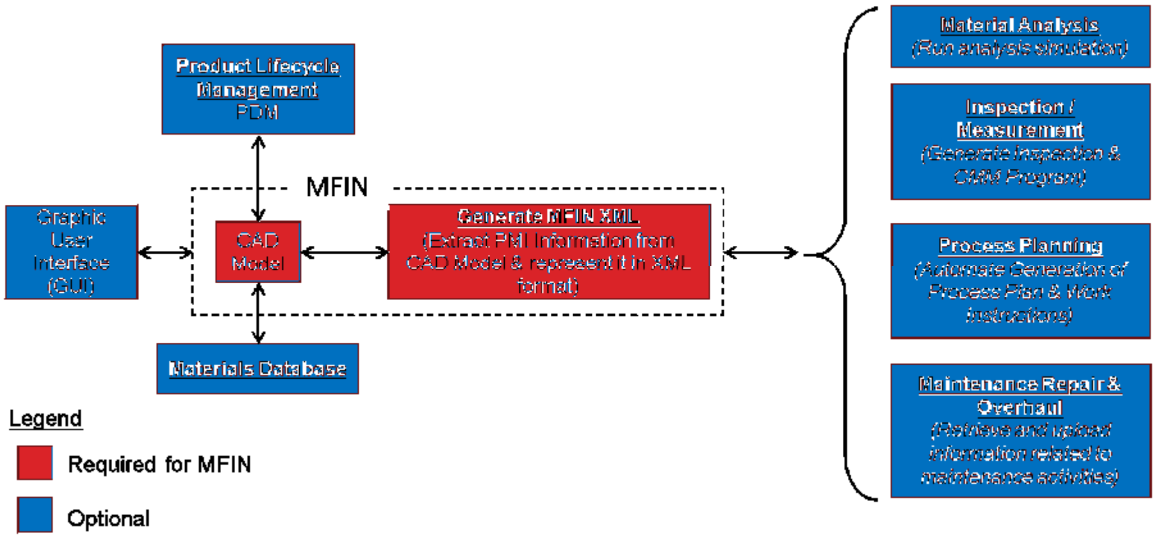

Figure 3 Representation of an MFIN architecture with optional elements

TARGET USERS & MODES OF OPERATION

The users of the MFIN will depend on where in the product lifecycle MFIN will be deployed. Section 3.1 of this document provides detailed descriptions of the use cases where MFIN was used for demonstration purposes of this project. The target uses identified included design engineers, analysts, process planners, inspection or quality engineers, sustainment engineers or field support specialists.

SOFTWARE DEVELOPMENT/DESIGN DOCUMENTATION

One of the primary goals of developing the MFIN framework was to eliminate interoperability issues. The decisions made during the development of MFIN were with the intent to select software agnostic solutions involving neutral or standardized formats and open-source programming platforms when possible in each of the use cases.

The MFIN framework in itself uses an XML structure which is a neutral format and is based on the ANSI standard QIF format. The schemas and linking mechanism used in the development was intended to incorporate all potential data types such as scalar values, strings/textual data, tabular data, functional data, external files hyperlinks and data from databases (specifically in material definition linking and analysis use case).

APIs were developed to interact with data (read or extract and write or create links) linked to a part model using the MFIN, with programming languages such as Python and C# (C Sharp).

The MFIN schema for material definition linking and the analysis use case enabled the creation of dynamic links to data of different types from the database and mapped on to features of the part for downstream retrieval and usage.

The extraction of the material data during analysis was done by using Materials markup language (MatML) which is another XML format for exchanging material properties. The current MFIN schema and framework demonstrates a working methodology for linking and retrieving materials information and analysis results for two types of features classified as (a) Solid topological entities (b) Point clouds (for location-specific properties).

However, the schema can be easily expanded by including different feature definitions in the same manner as the point cloud features were added onto the existing QIF feature definitions. Refer to the Implementation Guide for more detailed information. The MFIN APIs to extract data are generic and could be used by any analysis tool, requiring only the replacement of model building and results exporting process specific to analysis tools to be replaced.

The MFIN code was structured to accommodate as many formats of PMI as possible; however, there may be types of elements that were inadvertently not accounted for. The schema is easily modifiable to accommodate such situations should they arise.

In the provided sample files, python and C## were used to specifically to read, write, and edit MFIN data.

The MFIN GUI provided is intended to be an example only and will be customized by any company that will utilize the MFIN to meet their specific needs.

6. INDUSTRY IMPACT

The MFIN greatly improves the ability to access product, manufacturing, analysis, inspection and service data. The ease of accessing the data directly based on model features drastically reduces the amount of time needed to find, verify and use the data. It reduces the need to search multiple disconnected systems and provides linkages to the relevant data.

All industries will benefit from having direct access to their product data. Disconnected data wastes an extreme amount of time and leads to wrong decisions. While it does take time to configure the MFIN, the use of that data for years to come will outweigh the cost/time.

Most businesses (e.g. aerospace, automotive, medical) have similar Use Cases/Swim lanes in their lifecycle. Additionally, all businesses have data that need to be used throughout the product lifecycle. Having that data connected and available to users quickly can mean business advantages compared to competitors.

7. TRANSITION PLAN

NEXT STEPS & CHALLENGES

Model-Based Definition is not a new technology in and of itself. The difficulty in MBD/MBE implementations is in the systems integration side of things. Multiple different systems and even domains are to be connected, but the interface between them is often not well defined. This is part of what the MFIN project began to attempt to answer.

TECHNOLOGY DEPLOYMENTS

Lockheed Martin

Lockheed Martin’s Rotary and Mission Systems (RMS) has implemented a portion of MFIN capability as a proof of concept using a sample version of Capvidia’s software, MBDVidia to read MBD CATIA design information. The First Article Inspection (FAI) process began with design verification, generation of a QIF file, and exporting this data in the correct format using MS Excel. Capvidia’s software product, Pundit was then used to run CMM (Coordinate Measuring Machine) simulation tests. The next steps will be working with CMM vendors to best condition an interface to and from the CMM equipment using the QIF framework. These validations will initially be used by Quality and MFIN will be expanded upon in other business areas as needed.

Rolls-Royce

Rolls-Royce will implement the MFIN schema in 2020 during a pilot phase on one of their AE engine lines. This will include Analysis and MRO data with internal and external supply chain. Once successful with our AE pilot deployment, they will look to expand the use of MFIN further into their digital expansion.

Strategy for Integration of Project Outcomes

As a result of this project, establishing a standard for developing custom schemas could be beneficial to future projects that also want to leverage QIF. Such a standard would help shorten the learning curve for those new to QIF and would ensure format consistency as the QIF format expands to capture more types of information in the digital thread. Further development would need to continue to mature the MFIN framework and could allow the MFIN schema to become integrated into the QIF standard.

8. WORKFORCE DEVELOPMENT

To educate the workforce of the results of this project, Purdue University's Digital Enterprise Center will incorporate discussed of this technology into the Model-Based Definition Certificate Program and Technical Data Package Certificate Program. Course material will provide a high-level understanding of the framework and how the MFIN can be utilized to bring further benefit to a model-based approach that goes beyond PMI.

Video demonstrations were created and are available as part of the files available to the MxD community to help them understand the functionality better.

9. CONCLUSIONS & RECOMMENDATIONS

Development of the MFIN has allowed the team to demonstrate how a model-based approach can provide benefits beyond capturing PMI for quality purposes.

The MFIN has also demonstrated the ability to connect data at the feature level.

A pilot program using the MFIN at an OEM would be recommended to gather accurate metrics and to verify the perceived benefits due to error-prone manual data retrieval, and decreased time to perform tasks due to the seamless data exchange that has been established.

Development of a formal packaged solution potentially containing all files necessary to implement the solution would likely be required to gain widespread adoption of this technology. Integrating the MFIN schema into the existing QIF ANSI standard would benefit such efforts.

10. LESSONS LEARNED

Over the course of the project there were several lessons learned that were both technical in nature and around the area of general project management practices which are outlined below.

- The large size of the team on this project (around 40 people) made it challenging to come to a consensus at times. A smaller team or one representative from each participating industry partner may have helped streamline such decisions.
- The duration of the project (18 months) meant that several team members left the project (due to unrelated circumstances) and new members were added mid-stream. Assigning a project manager from MxD (to ensure that project management would be constant throughout the project) may have helped identify and capture requirements, identify project outcomes and milestones, and avoid the need to refer back to the original proposal to ensure the requirements were met.

- Requirements documents were needed to capture specific deliverables as intended in the initial proposal. Due to the large number and change of participants in this project mentioned above, incomplete or incorrect transfer of knowledge was a constant risk.
- Understanding the potential application of the MFIN for broad industry use cases was key to developing a solution that could be flexible.
- The time to learn how to use and interact with software products, scripting and programming languages and file formats need to be accounted for. A GUI was developed later in the project because the team realized that the MFIN is a hard concept for many to understand since it is “behind the scenes”. The risk of developing a GUI was that it might lead viewers to perceive that the MFIN is a packaged software solution. The team stressed that it was for demonstration purposes only when demonstrated at conferences or internal presentations.
- The GUI design process is not trivial and takes time and thought to implement. Including an experienced GUI developer on the project would have saved the team a considerable amount of time.
- Risks of running over schedule is present in almost all projects as it is difficult to estimate the time and effort to develop a solution using new technology.

11. ACCESSING THE TECHNOLOGY

This document was intended to provide a high-level overview of the solution. The outcomes of this project can be accessed via the MxD Membership Portal in accordance with your organization’s membership tier level. The documents listed below will be accessible on the portal and contain more detailed information on the prerequisite requirements (baseline infrastructure, commercial software licenses, etc.) and instructions for implementing and using the MFIN.

Implementation Guide

This document will walk through the detailed information needed to set up the systems and implement the technology for using the MFIN.

User Guide

This document explains the expertise needed to use the MFIN from an end-user perspective once it has been implemented.

Software Deliverables

Base MFIN

The following files are files to set up and install the base installation of the MFIN. Example files that were used in this project and for demonstration purposes are also included.

- QIF XML Schema files
- Scripts to handle communication between software tools and the MFIN
- MRO application with GUI
- Data analytics querying tool

These files were managed using Git and have been packaged in a .git file for full access to the Git repository as well as a .zip file to see the latest state of the code.

Process Planning Specific Files

(Under 06_SOFTWARE_DELIVERABLES in Sharepoint)

The following files are required to set up the process planning workflow in Teamcenter. Edits will need to be made to accommodate company-specific rules. Further development is required it the company is using a different database

- Siemens_ProcessPlanning11.4_DMDII-15-11.zip
- Install_Siemens_ProcessPlanning_MxD.docx
- MXD15-11-GenerativeProcessPlanning(withAudio).pptx

Video Demonstrations

On SharePoint

These videos will provide an effective way of communicating the results of an MFIN implementation in an easy-to-understand format, to scale the understanding to higher-levels of the organization and develop champions for implementing the technology.

12. APPENDICES

APPENDIX A: SAMPLE USE CASE: UNSCHEDULED MAINTENANCE

Remark: While the following use case is not an actual incident which occurred with the pump body housing used in this project, the scenario and the process are based on real life experience and similar situations.

Component:
The Oil Pump Body Housing contains and circulates lubricating oil under pressure to bearings, gears and shafts, removing heat from components.

Event:
An aerospace OEM experienced an in-flight oil pump failure which resulted in an engine fire and loss of thrust control. The airframe operator diverted to a nearby airport and made a successful emergency landing. The engine was removed from wing and sent to an overhaul shop for investigation.

Failure analysis:
The following information was retrieved using the MFIN and reviewed to identify the exact cause of the failure.

- Requirements documents
- Design & analysis data
- Manufacturing data
- Assembly & Inspection data
- Operating environment
- Maintenance history records

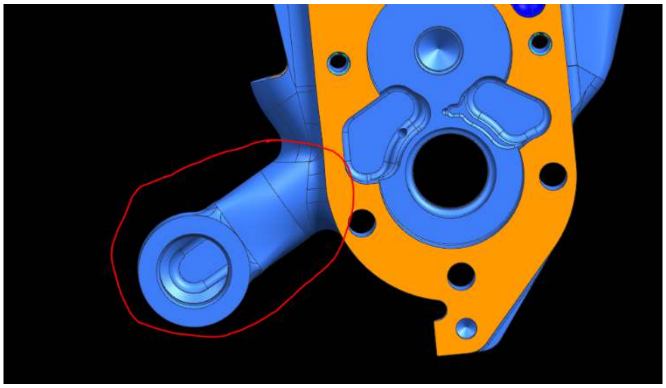

Figure 4 Location of oil leak on oil pump body

Conclusion:
A resonant frequency existed which caused an LCF (low cycle fatigue) failure of one of the passages which resulted in local cracking and induced oil leak. Oil came into contact with a hot surface resulting in the event.

Triage:
Safety analysis was performed segregating the 6,500 engines and operators to identify risk, exposure and reaction times. An Airworthiness Directive was issued by the OEM mandating maintenance action for a specified population.

Corrective Action:
A subsequent redesign was performed and a campaign enacted to replace all the defective pumps.

Corrective Verification:
To comply with ALARP (as low as reasonably practical), the OEM is mandating that overhaul shops inspect, measure, record, and report back status of the redesigned features of the new oil pump.

APPENDIX B: DEFINITIONS

What follows are a set of definitions, terms, and acronyms used in this document. These definitions were gathered from various source including the internet, reference papers, standards organizations, and the authors of these documents.

***[Term/Acronym]** – Definition or description*

[ANSI] – American National Standards Institute

[API] – Application Programming Interface

[BOM] – Bill of Materials

[C#] – C Sharp (programming language)

[CAD] – Computer Aided Design

[CNC] – Computer Numerical Control

[CMM] – Coordinate Measuring Machine

[Creo] - CAD software from PTC

[.dlls] – Executable file

[. jars] – Executable file

[FE, FEA] – Finite Element (Analysis)

[GD&T] - Geometric Dimensioning & Tolerancing

[GRANTA MI] – Materials database software from ANSYS

[GUI] – Graphical User Interface

[JSON] – JavaScript Object Notation

[MaterialCenter] – Materials database software from MSC Software

[MatML] - Material Markup Language (standardized file format based on XML)

[MBD] – Model-Based Definition

[MBDVidia] --- Model viewer from Capvidia

[MFIN] - Model-Based Feature Information Network

[MMPDS] -- Metallic Materials Properties Development and Standardization

[MRO] – Maintenance Repair and Overhaul

[MSC Nastran] – Finite element analysis software from MSC Software

[MxD] – The Digital Manufacturing Institute (Manufacturing times Digital)

[NX] – CAD software developed by Siemens

[Patran] -- Finite element pre/post-processor from MSC Software

[PDF] – Portable Document Format (file used to exchange information independent of software, hardware or operating system)

[PDM] – Product Data Management

[PLM] – Product Lifecycle Management

[PMI] – Product and Manufacturing Information

[Python] – High level interpreted programming language

[QA] – Quality Assurance

[QIF] – Quality Information Framework (standardized by ANSI)

[Sandbox] –Environment used to deploy software for testing before production deployment

[STEP] – Standard for the Exchange of Product Model Data (file format standardized by ISO)

[TDP] – Technical Data Package (all files needed to manufacture and inspect a part in one package)

[XML] – Extensible Markup Language (file format)