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Defining requirements for integrating information between design, manufacturing, and inspection

T. D. Hedberg Jr.[a], M. E. Sharp[a], T. M. M. Maw[b], M. M. Helu[a], M. M. Rahman[b], S. Jadhav[b], J. J. Whicker[b], and A. Barnard Feeney[a]

[a]National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.;
[b]The Manufacturing Technology Centre (MTC) Limited, Coventry, U.K.

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ABSTRACT
Industry desires a digital thread of information that aligns as-designed, as-planned, as-executed, and as-inspected viewpoints. An experiment was conducted to test selected open data standards' ability to integrate the lifecycle stages of engineering design, manufacturing, and quality assurance through a thorough implementation of a small scale model-based enterprise. The research team set out to answer: from design, through production, and final inspections, what are the hurdles that a manufacturer would face during the development of a fully linked and integrated information chain? The research team was not able to fully link all the required information, but value for industry was still identified. This paper presents the results of the experiment, provides guidance on how to overcome or mitigate identified challenges, and discusses the benefits or incentives to be gained from tracing or linking information through multiple stages a product lifecycle.

KEYWORDS
data interoperability; model-based enterprise; digital thread; digital twin

1. Introduction

To better understand and address the challenges faced in linking all stages of a manufacturing and design process, an investigative fabrication process was designed and enacted as part of a collaboration between the National Institute of Standards and Technology (NIST) and The Manufacturing Technology Centre (MTC). This collaboration sought to test selected open standards' ability to integrate the lifecycle stages of engineering design, manufacturing, and quality assurance through a thorough implementation of a small scale model-based enterprise (MBE). Lessons learned through this exercise have been recorded and digested in such a manner as to both inform further development of standards as well as encourage the adoption of the most useful and effective existing standards. In this paper, the primary standards of interest are ASME Y14.41, ASME Y14.47, ISO 16792, ISO 10303-242, MTConnect, and ANSI/DMSC Quality Information Framework (QIF). The activities and results of the collaboration

CONTACT T. D. Hedberg Jr. Current affiliation: Applied Research Laboratory for Intelligence and Security, University of Maryland. Email: thedberg@umd.edu

are described in this paper. The work of this collaboration builds upon past work and introduces novel contributions with studying a standards-based information integration from multiple sources using automatic data-alignment strategies.

At the onset, the most fundamental question and goal of this work was to understand the capabilities and limitations of implementing a standards-based information integration throughout the lifecycle of a product. From design, through production, and final inspections, what are the hurdles that a manufacturer would face during the development of a fully linked and integrated information chain? How can these obstacles be overcome or mitigated? What benefits or incentives can be gained from tracing or linking information through multiple stages of a product lifecycle – thus, creating a "digital thread" across the lifecycle? A digital thread is an integrated information flow that connects all the phases of the product lifecycle using accepted authoritative data sources (Kraft 2016; Hedberg Jr et al. 2016; Wardhani and Xu 2016). The digital thread focuses on integrating all phases of the product lifecycle for making efficient and effective measurements of the lifecycle in support of data-driven methods (Hedberg, Bajaj, and Camelio 2020).

While we explored the research questions around the goals of this work, the results of our research point to the reality that a standards-based information integration in not achievable today because the standards do not data-alignment strategies without significant human intervention. Our results show that the popular data standards used in industry do not support automatic data alignment. Therefore, instead of documenting implementation schemes, we provide recommendations to the Standards Development Organizations (SDOs) for enhancing the standards that we expect would enable automatic data-alignment capabilities. We also expect that once automatic data-alignment capabilities are realized, researchers should then be able to discover methods for implementing and transferring standards-based information integration to practice.

2. Background

During a survey of the current state of the industry, as well as first-hand experience during the exemplar manufacturing collaboration designed for this work, we found that the alignment of information across lifecycle stages is primarily accomplished with intense amounts of human labor, if at all. At the date of this publication, there is still not a broadly applicable process or tool that allows for the automation of information alignment and cross-stage analysis that can link multi-stage information. An example of such an information trace would be to correlate as-measured data (QIF) backwards through as-fabricated (MTConnect), as-planned (NC Code), and as-designed (STEP) data to aid in determining the source of production defects (e.g., design flaw, equipment degradation). Given this lack of standardized method for linking between the manufacturing process stages, this paper describes our experiment exploring avenues for automating the process and provides recommendations and requirements for integrating this information.

2.1. *Manufacturing Standards*

Throughout the lifecycle of a manufactured product, there are a plethora of standards that information and data associated with that product are subject to. This makes the integration of such data exceedingly challenging as few of these standards were created with interoperablity in mind, instead each being designed for its own specific purpose. This section reviews many of the standards relevant to lifecycle product production. In order, the review includes: ASME Y14.41, ISO 16792, ISO 10303-242 (STEP), MTConnect, and ANSI/DMSC QIF. It should be noted that this is not a complete list of standards applicable to a computer-numerically controlled (CNC) manufacturing process; many different standards could have been used in addition or as an alternative to those reviewed here.

2.1.1. Standards for Design Requirements in Digital Drawings

With the uptake of computer-based design software, the American Society of Mechanical Engineers (ASME) released ASME Y14.41 to define requirements of model-based product definition in computer-aided design (CAD) software (American Society of Mechanical Engineers 2019). Focusing primarily on geometric dimensioning and tolerancing, ASME Y14.41 presents methods for organizing product definition data within a CAD file and was created primarily to allow CAD information to become an additional resource for manufacturing and inspection criteria. Where applicable, it recommends annotating the model with design requirements in three-dimensional (3D) space near the associated geometry, or in some cases, additionally using an engineering drawing graphic sheet to indicate requirements.

The ASME Y14.41 is a trusted standard of industrial practices for a company to best utilize digital CAD information. This standard allows for cross interpretation between design, machining, and inspection aspects of the product lifecycle. This standard became the basis for the international standard ISO 16792:2006 (International Standards Organization 2015).

Like the ASME standard, ISO 16792 prescribed requirements for documenting 3D digital models. The rules include requirements for preparation, revision, and presentation of digital product definition data. Many of the explicit requirements address elements that are significantly different, or not included in older standards for drawings. Our model-based definition (MBD) data made use of syntactic notes and annotations connected to semantic geometric dimensions and tolerances (GD&T) and 3D annotation views or presentation states as is mandated by the ASME and International Standards Organization (ISO) standards.

An additional document, ASME Y14.46 (American Society of Mechanical Engineers 2017), is a draft standard for trial use and seeks to extend the design rules to describe complex parts, and features unique to additive manufacturing.

2.1.2. Standards for Design Information

The international standard for describing product data in a computer interpretable manner independent of the construction software is defined in ISO 10303-242 (International Standards Organization 2014). STandard for the Exchange of Product Model Data (STEP) is designed for exchanging files between software used at different stages of the product lifecycle, including: CAD, computer-aided engineering (CAE), computer-aided manufacturing (CAM), computer-aided inspection (CAI), product-data management (PDM) / enterprise data modeling and other computer-aided technologies (CAx) systems.

In this project we used the STandard for the Exchange of Product Model Data Application Protocol 242 (STEP AP242) standard to drive the CAM process. We started with native SolidWorks CAD files and created derivative STEP AP242 models from this. The same native format was also used to create QIF files which were used

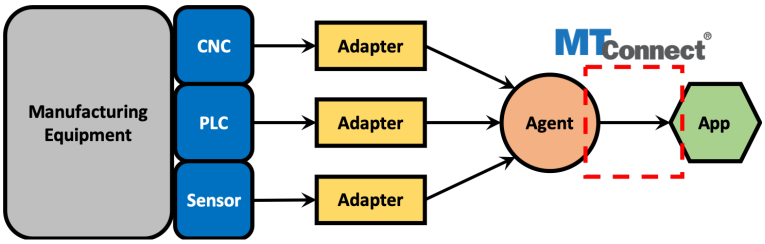

Figure 1. Overview of basic MTConnect architecture; the standard only specifies the output of the Agent as highlighted by the red-dashed box (after Sobel (2015)).

in the measurement parts of the workflow.

2.1.3. Standards for Manufacturing Information

MTConnect is an American National Standards Institute (ANSI) accredited open, read-only, and extensible data-interoperability standard that offers a vocabulary and relevant semantics for manufacturing equipment to provide structured, contextualized data with no proprietary format (MTConnect Institute 2018). Figure 1 shows the basic MTConnect architecture. An Adapter is an optional piece of software or hardware that collects and filters data from a device and publishes this data to an Agent. An Agent is a Hypertext Transfer Protocol (HTTP) server that provides a Representational State Transfer (RESTful) interface for a client application. It organizes and manages data from one or more adapters and creates and publishes a response document based on requests from a client.

During the work presented in this paper, we used the MTConnect standard to extract data from the CNC machine to capture key manufacturing parameters. This standard enables conversion of raw machine data to a machine-readable format for further analytics to be carried out. Investigations have been reported into applying the standard to large scale production facilities including aircraft production (Venkatesh et al. 2016).

2.1.4. Standards for Quality and Inspection Information

QIF is an ANSI accredited that aims to enable seamless flow of information within computer-aided quality measurement systems (Digital Metrology Standards Consortium 2018). QIF supports metrology data from all areas of the process chain, from design, through inspection and measurement resource planning, to execution, results evaluation, and statistical analysis.

As with the MTConnect standard, QIF files are based on Extensible Markup Language (XML) enabling them to be integrated easily with other applications, including Internet and network-based applications. The QIF standard is used throughout this experiment to govern the flow of information from the design through to measurement stage. An illustration of data flow taken from the QIF standard documentation is shown in Figure 2 (Digital Metrology Standards Consortium 2018).

Unlike many other standards considered, the QIF XML schema used to define the file formats are considered part of the standard. Therefore, an implementation of this standard not using the schema fully would not be conforming to the standard. This is of particular relevance for standardization, interoperability, and automation tools. It means that the difficulties experienced with the integration of other data standards is less likely to affect the QIF standard. As more companies adhere to this standard, the

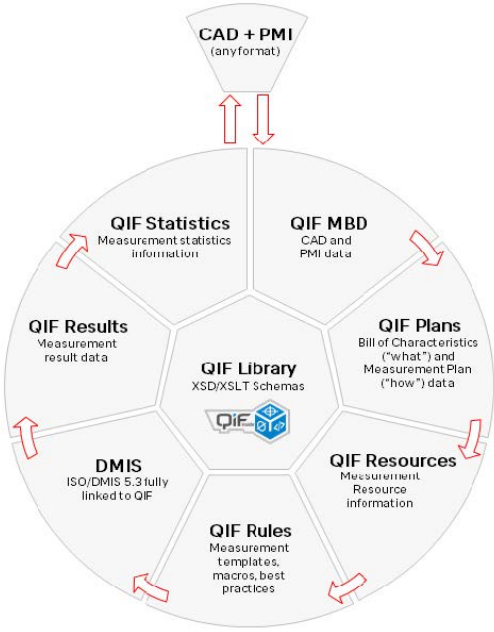

Figure 2. Overview of basic QIF information architecture; around the QIF core library are the six QIF application-specific information models, Model-Based Definition (MBD), Plans, Resources, Rules, Results, and Statistics (reproduced from Digital Metrology Standards Consortium (2018)).

market will see a reduction in variability of commands that exists between different equipment vendors allowing for more concise and broadly applicable software solutions to be developed.

2.2. *Technology for Manufacturing Integrating Information*

There are many existing technologies that aim to facilitate or augment the integration of production lifecycle information. Investigations into these technologies showed that a majority of off-the-shelf products have limited scope and are not structured to enable automated cross-domain (e.g., design, fabrication, inspection) data alignment. As additionally shown through our work on this paper, significant effort is required to manually align data. Our efforts revealed both strengths and weaknesses of the existing technologies in extended previous work and automate some level of data alignment to enable information mining and data analytics.

2.2.1. Model-Based Enterprise

Information technology advances (e.g., data analytics, service-oriented architectures, and networking), coupled with operational technology (e.g., hardware and software for sensing, monitoring, and control of product and processes), have enabled a digital revolution promising to reduce costs, improve productivity, and increase output quality (Childerhouse and Towill 2011; Wu et al. 2013). These two facts are motivation for why the manufacturing sector of industry is working to connect each phase and function of the product lifecycle. We recognize that the problems and promises are not novel, but rather emerging technologies are now available that enable novel approaches to implement solutions that may have been ahead of their time (Mckay 2003; Wang, Ong, and Nee 2018). The advances information and operation technology have coalesced into an effort being called MBE.

MBE is represented be several constituent components. A workshop titled "MBx: Peeling Back the Layers of MBE" conducted during the 2016 MBE Summit (Carlisle 2016), set out to define several critical components of the MBE that included design, engineering analysis, manufacturing, systems engineering, sustainment, testing, evaluation, and quality. Our work presented in this paper was most concerned with MBD, model-based manufacturing (MBM), and model-based quality (MBQ). The following are the proposed definitions from the workshop for MBD, MBM, and MBQ:

MBD: The authoritative digital-data set based on a 3D geometric model that defines the end-item requirements for a product.

MBM: An environment [in that] the Design Data can be consumed by the value stream to plan, produce, fabricate, assemble, inspect and certify, [and] maintain and sustain parts and assemblies to meet requirements.

MBQ: The conformance of the physical product and process to the requirements of digital product definitions and process specifications using measurement planning, execution, and evaluation in combination with 3D annotated models and associated data.

The MBD, MBM, and MBQ domains have different data requirements, such as the identification of shape, features, and characteristics. MBE requires adopting model-based data standards to effectively integrate the different kinds of data for efficient reuse and exchange between product-lifecycle phases (Hedberg Jr et al. 2017a). However, traceability of requirements and activities is paramount to ensuring effective functioning supply chains (Khabbazi et al. 2011). Moreover, data interoperability between design activities (e.g. product and assembly design) and manufacturing activities (e.g. fabrication, assembly, and quality assurance) must be consistent (Hedberg Jr et al. 2017b). Hedberg Jr et al. (2017b) recommend using ISO 10303-242 (STEP AP242) (International Standards Organization 2014) to represent the as-designed configuration of products and MTConnect and QIF to represent the as-fabricated and as-measured configurations. Aligning these three representations would enable quicker and easier knowledge building based off experience in the product lifecycle. The goal of our work here is to evaluate the capability for integrating various types of standards-based data available in the MBD, MBM, and MBQ domains – particularly MTConnect and QIF.

2.2.2. Data Mining

A well annotated and aligned set of integrated data is necessary for extracting vital information that might otherwise be inaccessible or impractical to synthesize. For example, using appropriate techniques, integrated data could be used to obtain knowledge of the factors influencing the quality of production parts. This in turn could be translated into actionable information or policies to improve quality and or production efficiency. The capture and contextualization of such actionable information is directly linked to data mining across the lifecycle stages to produce information about a process.

Several studies (Fischer et al. 2015; Hedberg Jr et al. 2016; Trainer et al. 2016; Hardwick and Sobel 2017) investigated integrating MBE components and/or standards-based data. Hedberg Jr et al. (2016) compared paper-based processes to model-based processes and identified a potential savings of 75 percent in cycle-time. Fischer et al. (2015) and Trainer et al. (2016) also compared paper-based processes to model-based processes using STEP AP242 to study the return-on-investment benefits and develop tools for closing some gaps identified by Hedberg Jr et al. (2016). Lastly, Hardwick and Sobel (2017) automated measurement of producing a product using semantic tolerances, requirements sent using STEP AP242, measurements streamed using MTConnect, and results returned using QIF.

To utilize all these varied data sources and structures, robust algorithms must be identified and tested. A variety of data mining techniques that have been identified as strong candidates for use in manufacturing include clustering, classification, regression, and decision-tree learning (He et al. 2009; Liang 2015). Case in point, decision-trees have been shown to be effective in improving yield in the manufacture of semiconductor devices (Chien, Wang, and Cheng 2007) and for drawing qualitative links between manufacturing parameters and the geometrical forms of drilled holes (Mason, Rahman, and Maw 2017). Recently the use of regression-tree learning has also been demonstrated as an effective technique for predicting part quality (Maw, Whicker, and Rahman 2017). These techniques may be feasible for optimizing the accuracy of features on the part in our and future investigations.

3. Methodology

The goal of this work is to explore and quantify the capabilities of integrating data and information between design, manufacturing, and inspection. As part of this, a secondary effort focused on identifying key process variables for determining optimal manufacturing parameters. MTC played the role of an original equipment manufacturer (OEM) and NIST played the role of a contracted design house and manufacturer. The test case was an assembly designed with input from both parties and was manufactured at NIST. Each component of the assembly also underwent a first-article inspection and 100 percent inspections at NIST. Data was collected at each step in the workflow – STEP AP242 and NC Code sheets for design information, MTConnect from manufacturing data, and QIF for quality data. The assembly components were then shipped to MTC, where an incoming and receiving inspection was conducted. The aim in this process was to determine the ability to effectively and efficiently integrate the data collected throughout this process.

The success criteria was identified as the ability to automatically align the features and characteristics across each data set. ASME Y14.5-2009 (American Society of Mechanical Engineers 2009) standard defines a feature as “a physical portion of a part such as a surface, pin, hole, or slot or its representation on drawings in models, or in digital data files.” ANSI/QIF Part 1-2015 (Digital Metrology Standards Consortium 2018) standard defines a characteristic as “a control placed on an element of a feature such as its size, location or form, which may be a specification limit, a nominal with tolerance, a feature control frame, or some other numerical or non-numerical control.” A design of experiments (DOE) is leveraged to induce variability in one of the parts in a structure. The DOE should enable linking any variability to its source. Any linking requires aligning data about the features and characteristics.

Our work builds on the previous studies, but includes some novel additions. First, our work is the first investigation that used an assembly in the experiments. Reviewing the literature, all past model-based studies used single components as their test cases. Studying an assembly introduces a more realistic level of product complexity. Industry applies tolerances to features in definition of product components because those components must fit together in an assembly to realize the product. Studying only the data of a single component does not provide the full context in the overall quality of the assembly. Therefore, industry must review the quality of all components of a product and the relationship of each component to the assembly for understanding the quality of the product.

Second, our study tests data integration from multiple sources. The design and QIF data come from multiple vendors, suppliers, and tools. Collecting and integrating data from multiple sources is closer to a real MBE supply chain. More closely matching a real supply chain is a significant enhancement over previous work.

3.1. *Design of the Digital Assembly Definition*

Test cases from the NIST "MBE PMI Validation and Conformance Testing Project" (Lipman et al. 2017) were the starting point for the design of the assembly used in our study. Specifically, we used Fully-Toleranced Test Cases (FTC) 7 (box), 8 (lid), and 9 (mounting plate) (Lipman 2017). The decision to start with the FTC models was because these models had already undergone expert review and were designed to be an assembly. This minimized the time required to develop a valid assembly for our work.

While we started with three models, we did make a few changes to ensure the assembly would meet all the needs of our study. First, we scaled down the original size of the designs to reduce the cost of the manufacturing step by allowing us to utilize a smaller 3-axis mill that had time available in its production schedule. Second, we added some additional features to all of the parts to increase the diversity of the types of characteristics. Lastly, we converted each design to standard metric units since the original designs used imperial units.

The complete assembly is comprised of the box, lid, and mounting plate, derived from the FTCs, an acrylic window to mount in the lid, and standard hardware procured through a third-party. All data from the work presented here, including the CAD models, are available in a published data set from Hedberg Jr et al. (2018).

No two-dimensional (2D) drawings were produced for the assembly or its components. All the product definition was included as product and manufacturing information (PMI) in the 3D CAD model. PMI included the typical information included historically on a 2D drawing, including dimensions, tolerances, and notes. PMI, in models, also includes meta-data stored as model attributes. Embedding the PMI in the CAD model enables shorter planning cycles in both manufacturing and inspection. For example, the inspection planner can use tools that read the characteristics' requirements directly from the model. This eliminates the need for manual, human-based data entry, which also reduces the risk of injecting errors into the process. Also, PMI added to the model, in accordance with the ASME Y14.41-2012 (American Society of Mechanical Engineers 2012) standard[1], will provide additional functionality to the user – the features associated with the PMI will highlight when selected by the user. 3D geometry combined with PMI provides a rich set of capabilities where both a computer and a human have interpretable information available for consuming the digital product definition in a process.

[1]The 2012 edition of ASME Y14.41 was selected because the latest edition was not publicly available at the time the models were generated in this work.

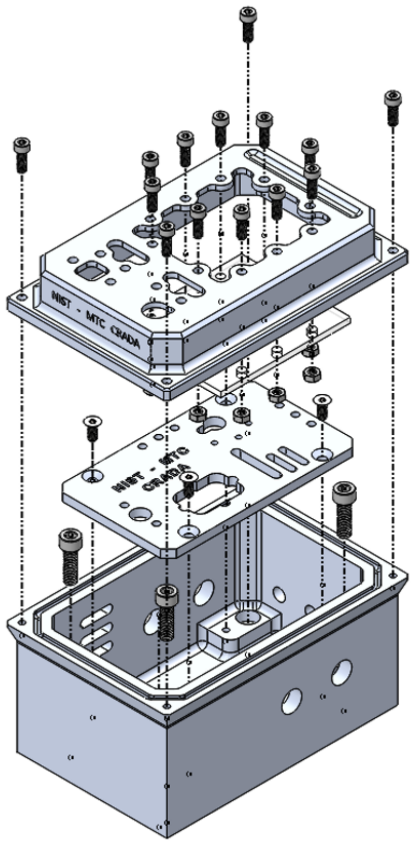

Figure 3. Presentation of the Exploded View, as displayed inside the CAD system, of the assembly test case showing all components

3.2. *Design of Experiments for Manufacturing Parameters*

The influence of machining-process parameters on the quality of the final product is a complicated problem to model. Rather than modeling the problem, a DOE was proposed to control the parameters of data that would allow for the identification of strong correlations of machining parameters for this particular case. The experiment focused on the 16 hole features on the plate within our assembly.

We wanted to analyze the form error of the manufacturing process above the noise in the machining (and measurement) process. We decided not to make entirely identical parts as this would likely only achieve one single manufacturing signature type and background noise. The process parameters were changed sufficiently to distort the parts above the noise level and produce multiple manufacturing-signature types. The aim was to understand how much these process parameters affect variation in the part.

Tool length, tool speed, and feed rate were the three parameters chosen to be controlled for pocketing processes during the experiment to produce variation in the quality of the part. These parameters were identified as being the ones that are commonly varied in machining to modify the part. Initial values were specified at the recommended settings for given tools and component material. Each variable then had either one or two varied states to induce part variation. The variations were controlled to ensure the full parameter space is covered systematically rather than varying parameters based on a random choice. Table 1 shows the DOE matrix, where "*" markers indicate the mean value between maximum and minimum manufacturer recommended values. Additional labels indicate the varied states of the respective parameter.

The DOE approach provided a reduced number of parameter sets and reduced number of variants of each control parameter. Confidence in the results and the repeatability of the process would come from analysis of the quality of the holes as a group.

Mason, Rahman, and Maw (2017) showed that the tool length, tool speed, and feed rate are critical variables within the drilling of holes in mild steel components. Understanding the sensitivity of each control parameter with regard to how much effect its variation has on the final part made of aluminum, relied on expert knowledge of the machining specialists. The values used for each tool used for the manufacture of these parts can be found in Table 2.

A new cutting edge was to be used at the start of every component such that tool wear can be reduced and monitored. Temperature and humidity readings were recorded at the start of production for each component. Fixturing was only done once after the initial material-preparation phase was completed. All subsequent machining operations were performed in-station to minimize alignment errors.

3.3. *Manufacturing and Inspection Planning and Execution*

Both manufacturing and inspection planning were completed using model-based methods. We used commercially available software to program the fabrication and inspection programs. The various software packages were selected for their "off-the-shelf" support of the QIF standard and required no customization.

The CAD models were imported directly into the planning software with each model's PMI utilized to the fullest extent supported by the software packages. The fabrication program's paths and tooling selections were automatically determined by the CAM software when possible, but the majority of the decisions were made by the machining specialist based off his experience and knowledge. A numerical control (NC)

Table 1. DOE design matrix

Part Number	Tool Length	Cutting Speed	Feed Rate
01	Short*	Fast*	High*
02	Short*	Fast*	Medium
03	Short*	Fast*	Low
04	Short*	Medium	High*
05	Short*	Medium	Medium
06	Short*	Medium	Low
07	Short*	Slow	High*
08	Short*	Slow	Medium
09	Short*	Slow	Low
10	Long	Fast*	High*
11	Long	Fast*	Medium
12	Long	Fast*	Low
13	Long	Medium	High*
14	Long	Medium	Medium
15	Long	Medium	Low
16	Long	Slow	High*
17	Long	Slow	Medium
18	Long	Slow	Low
19	Operator's Choice	Operator's Choice	Operator's Choice
20	Operator's Choice	Operator's Choice	Operator's Choice

*Recommended Value

Table 2. Process parameters for pocketing process of holes in the DOE

Tool Name	**Tool Length**		**Cutting Speed**			**Feed Rate**		
	Short*	Long	Fast*	Medium	Slow	High*	Medium	Low
	Inches		Revolutions Per Minute			Inches Per Minute		
0.093 inch End Mill	0.375*	1.375	12k*	9k	6k	36*	27	21
0.125 inch End Mill	0.375*	1.375	12k*	9k	6k	36*	27	21
0.25 inch End Mill	0.5*	1.5	12k*	9k	6k	140*	110	80
0.5 inch End Mill	0.75*	1.75	12k*	9k	6k	140*	110	80
0.5 inch Counter Sink	1.0*	2.0	1k*	0.75k	0.5k	2*	1.5	1
3.0 inch Face Mill	n/a	n/a	5k*	3.75k	2k	120*	90	60
0.125 inch Engrave	0.375*	1.375	12k*	9k	6k	40*	30	20

*Median Recommended Value

program was generated and post-processed for the 3-axis mill fabricating the parts. Machine and process data was captured during the program run using MTConnect-compliant adapters and agents.

For the inspection, the NIST coordinate-measurement machine (CMM) was programmed automatically using the CMM manufacturer's programming tool. The programming tool read the characteristics directly from the CAD model's PMI, determined the needed CMM-probe configurations, and generated an execution-time optimized inspection program. The time to generate the first-article inspection programs for each part took less than ten minutes per part. The measurements and inspection results were captured in a database in real-time and then exported as QIF Results at the completion of the inspection.

The MTC CMM was a different manufacturer from the NIST CMM. The MTC CMM was programmed using a combination of third-party software package and the Dimensional Measuring Interface Standard (DMIS) for execution. The CAD model was translated into QIF MBD and imported into the third-party software. The software automatically read the PMI, recognized the features and characteristics for inspection, set datum structures, and assigned both a lightweight point strategy and simple scan strategies to the features. The CMM program was exported to DMIS 5.2 for execution on the CMM. The measurements were exported from the CMM manufacturer's software to a DMIS *.out* file. The DMIS measurements file was imported to the third-party software and the inspection results were exported as QIF Results.

3.4. *Data and Information Flow*

Integrating data from different sources is critical to extract information and knowledge which contains links between the manufacturing parameters and the final quality of features on the part. For example, to draw a link between the part quality and machining parameters at a specific time, it is necessary to obtain both measurement data (in QIF format) and machine parameters (encoded in the machine's G-Code) in the same format to carry out further operations. Once this has been carried out it is also imperative that the integrated data is stored in a format that is easily readable by the software carrying out data mining. The format of the final information in the knowledge base must be easily readable by both humans and machines; a format such as comma-separated value (CSV) is most appropriate as this is easily read by commonly used data analysis software such as Microsoft Excel, Matlab, R, Python and any other analytics tools.

An important element of the data flow is the monitoring and collecting of NC-Code execution data from the CNC machine using an MTConnect adapter. This data contains in-process measurements of important machining parameters including feed rate and tool-rotation speed. By converting this to simulated G-Code, it is possible to determine the machine parameters at a given time. This level of traceability is essential to any data-manipulation operations as it enables data mapping to be carried out.

This traceability also gives a mechanism to make comparisons between the predefined parameters such as tool length, tool speed, and feed rate specified in the machine's code and the actual values of these parameters recorded in-process. Part quality could then be linked to both the parameters specified to the machine and the true values of these parameters as measured in process. This step is currently being investigated further as the tools to perform such an action are not available. Development of such tools is an important step to automate the process and enable data analytics for the

Table 3. QIF Results for Aprox. 20 Assembly Units

Assembly Item	Failed Tests	Mean % Deviation From Nominal	Number of QIF Tests	Units Tested
Box	0	33.74%	47	18
Cover	1	12.46%	27	20
Plate	51	33.63%	31	20

extraction of knowledge.

Figure 4 illustrates the data flow throughout the data capture stages, including the different sources of data and the different standards which these data fall under. MTConnectR, a package within the R high-level programming language designed for statistical analysis (Joseph et al. 2017), was used to convert the extracted process data from the CNC machine code to the MTConnect XML format. The specific machine tool used to produce the parts did not report tool-path positions. Therefore, the MTConnectR package was also used to simulate the tool-path position and align it to the collected execution data using a dynamic time warping method (Helu, Joseph, and Hedberg 2018). The resulting data output and alignment from the MTConnectR package provided a structured dataset that was used in the data-mining portions of the study.

4. Results

All of the data collected in this study is available in Hedberg Jr et al. (2018). The analysis of the produced parts centered around relating the machining input parameter specifications to the end quality measurements. The specific design features from each part could not be autonomously aligned with the recorded QIF tests due to inconsistent naming conventions between the separate sources of information. Despite this, there is much that can be learned from the analysis of the quality features for each of the separate parts produced.

4.1. *QIF Results*

During the course of this work a total of 20 assembled units were machined with QIF test results taken on each of the manufactured units. Of the three parts of the assembly, the Box exhibited zero quality test failures, the Cover showed one, and the Plate returned a total of 51 failed tests across the 20 units manufactured. From the results listed in Table 3, we can see that although the Plate had the most quality test failures (deviations found to be beyond the specified tolerances), the Box had the highest average deviation from nominal across all tests.

To some degree, the failures within the Plates were expected as the machining parameters were varied beyond recommended values to help correlate them to resulting quality. However, as seen in Figure 5 the quality results from the Box units show a strong bi-modal distribution for many of the captured test, with 14 of the 47 tests showing strong tendencies to be at the lower end of the allowable tolerance values. Almost all of these poor test results relate to the positioning of the respective feature. As the large deviations from nominal are consistent across all the units tested, the poor quality issues could be a result of bad tolerance selection, inadequate machining capabilities, or some other mis-specification of the machining parameters. By moni-

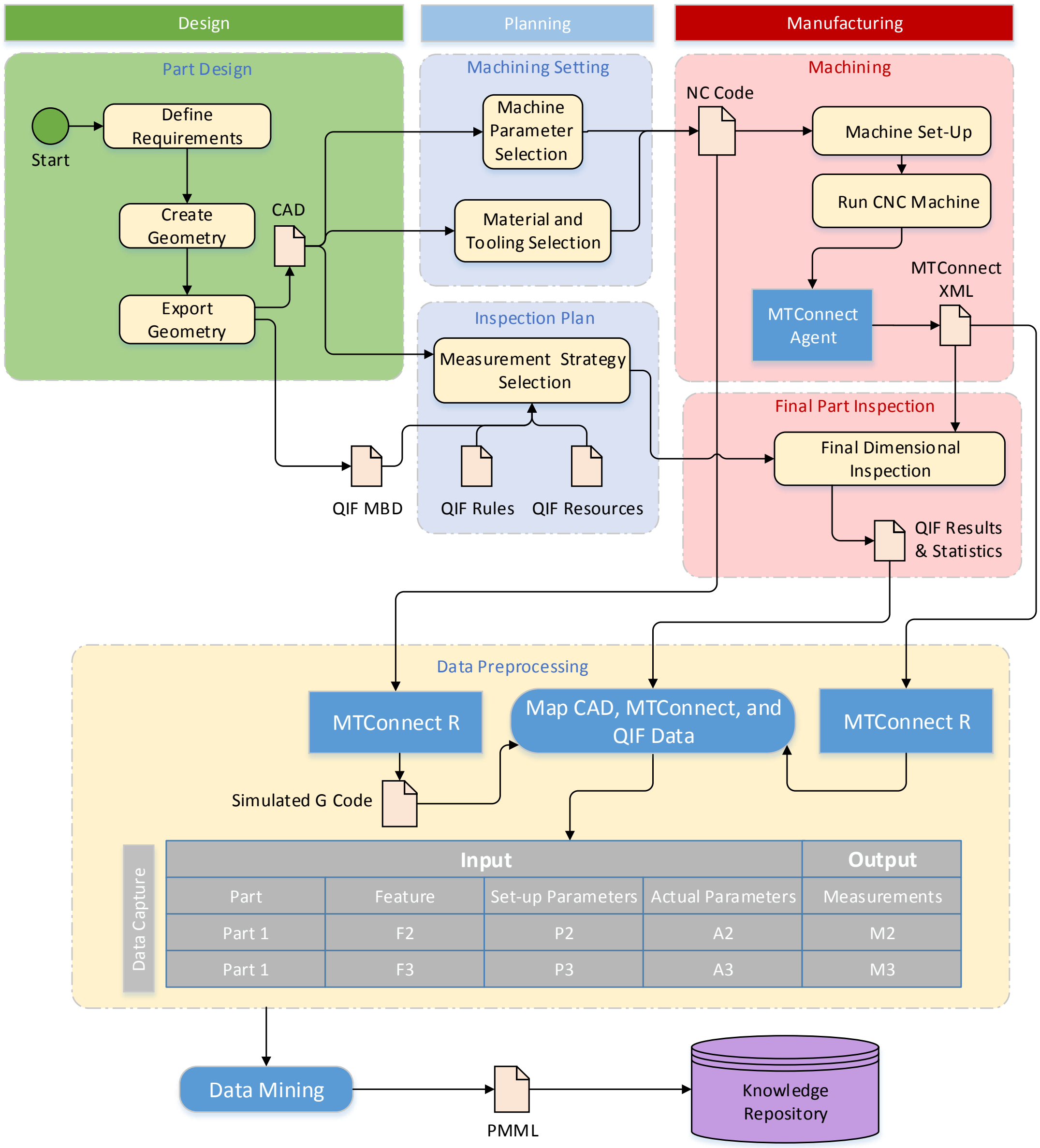

Figure 4. The flow of data and information within this investigation. The diagram shows data flows between the design, planning, and manufacturing phases. The data is then combined in the data preprocessing task to support the data mining and knowledge building activities.

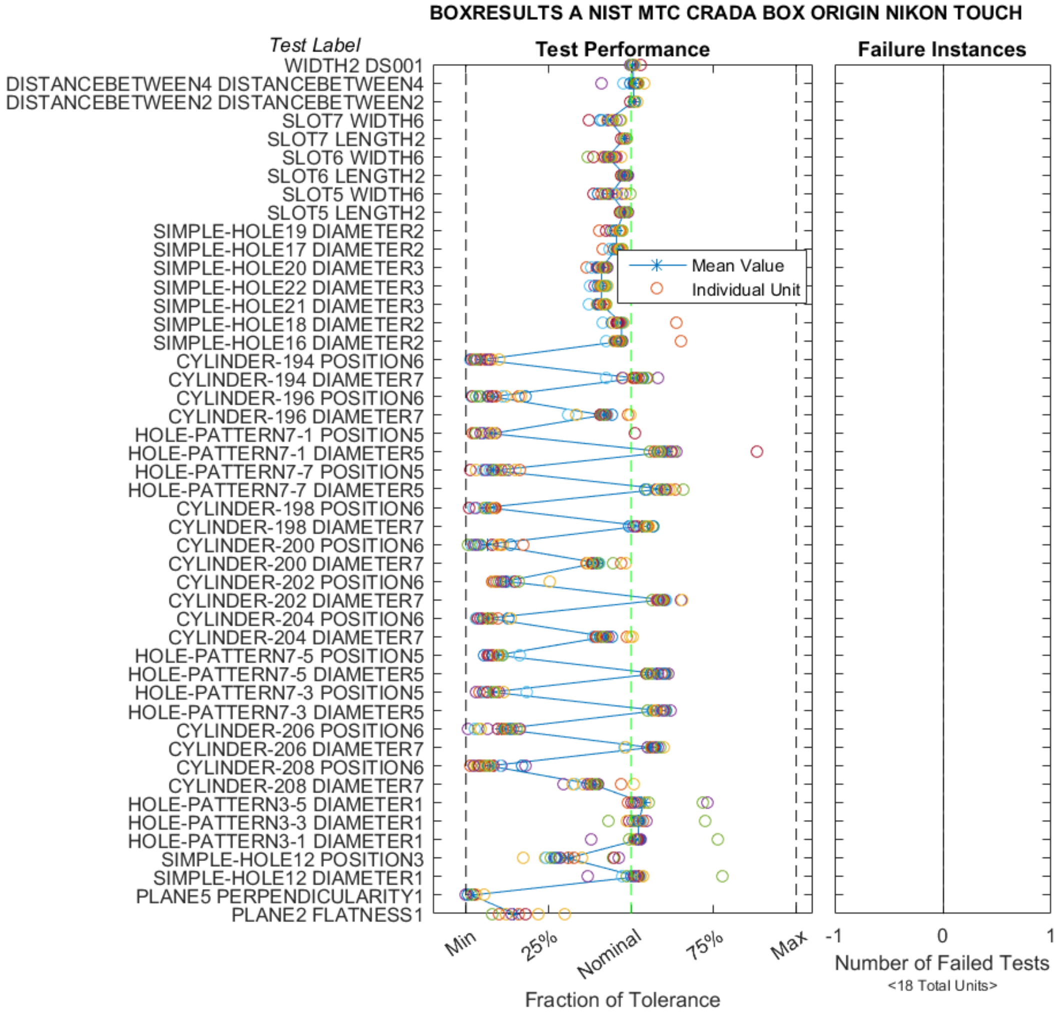

Figure 5. QIF Test Results for Individual Box Units as Percent of Tolerance Span

toring for such anomalous quality behavior despite a lack of failures, an investigation could be triggered to not only help trace down the problem, but perhaps suggest a solution.

Conversely, the test performance for the 20 Cover units was very strong across nearly all tests. Of the 27 individual quality tests performed, only one showed deviations more than approximately 10 percent from nominal, and the large majority less the five percent. Of those tests found to show large deviations, only one exhibited a grouping largely not centered near nominal. Strangely perhaps, the test with the worst average deviation did not produce a failure. Again, such anomalies can be monitored and trigger deeper investigations. A full description of the Cover QIF results can be found in Figure 6.

The quality test deviations in the Plate units show a stark increase in the number of failures compared to those found in the other assembly parts, particularly in six of the total 20 Plate units tested. Figure 7 shows very clearly that the units labeled 10-18 have a clear increase in the average quality deviation and number of failures. Not coincidentally, this corresponds to the parts listed in Table 1 as using the "Long" tool

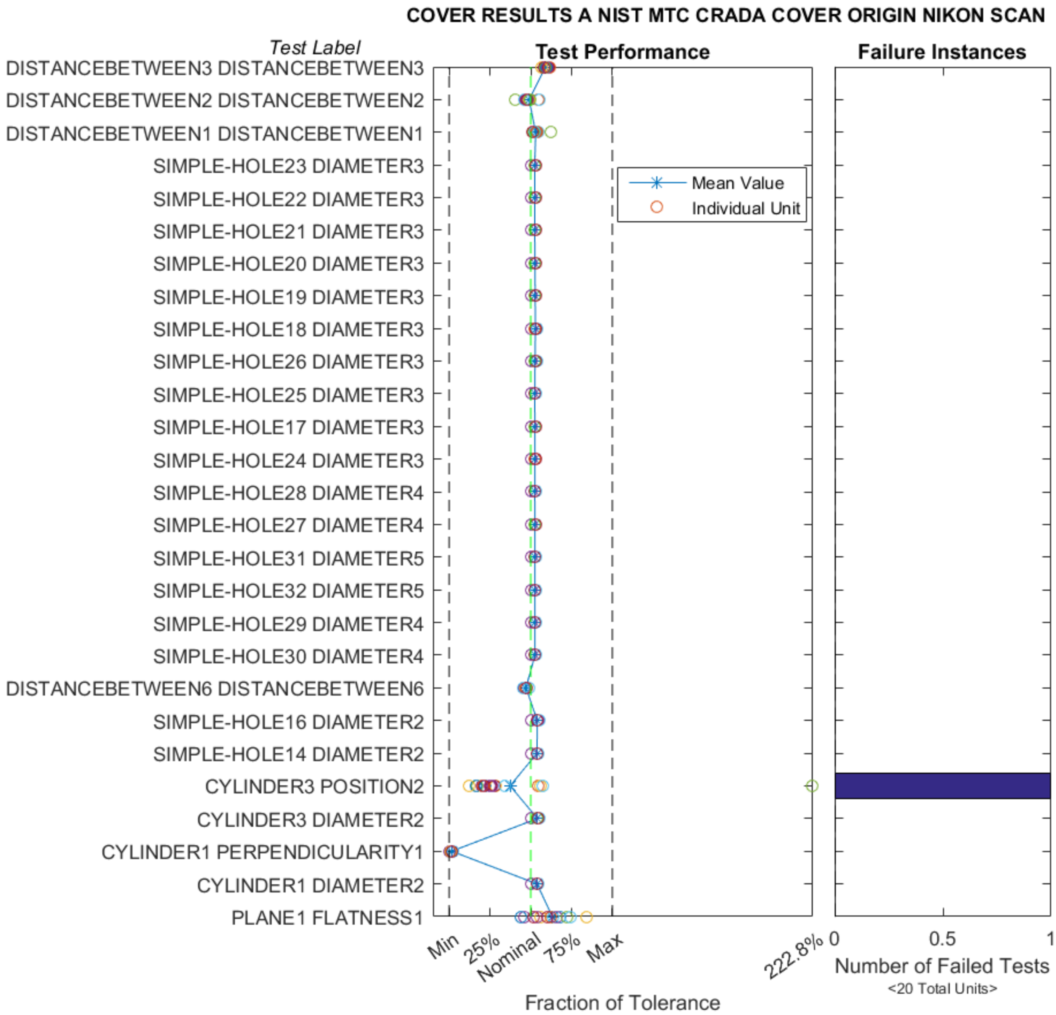

Figure 6. QIF Test Results for Individual Cover Units as Percent of Tolerance Span

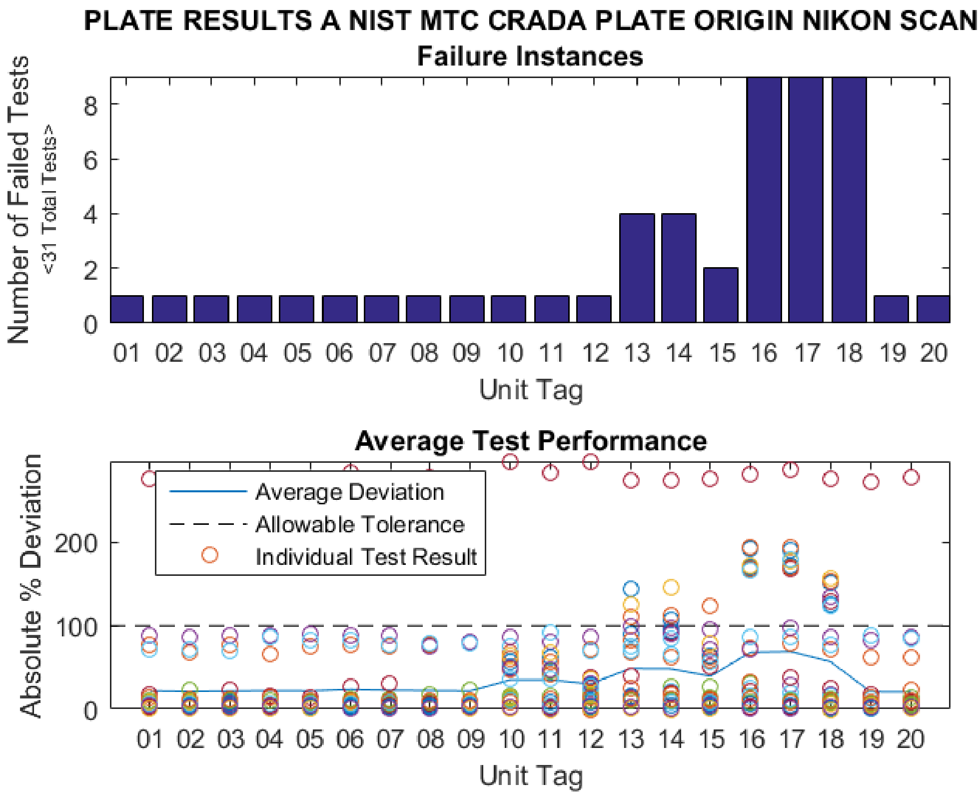

Figure 7. QIF Test Results for Individual Plate Units as Percent of Tolerance Span

lengths. A more detailed analysis matching machining parameters to quality within the Plate units is presented in the next section.

A very notable test failure is the "Cylinder 3 Radius 1" test (see Figure 8). All 20 of the manufactured units failed this test regardless of the various machining parameters employed during the manufacturing. This lends highly to the supposition that the error is derived from some requirement of the design. This could be a tolerance misspecification, a feature that is not obtainable with the current plant machinery, etc. By directly linking the feature identified with this test to a design side feature, quick investigations into alterations can be created early in test production runs of new products.

It is interesting to note that all three assembly structures exhibited some of their worst quality test performance in tests relating feature position, perpendicularity, and flatness. this could indicate a shortcoming of the tolerancing, the ability of machines themselves to produce these features, or in the equipment used to measure these tests. Given that the respective units were produced on multiple machines with different manufacturers, this would tend to indicate either incorrect tolerancing or testing ability. Directed and coordinated analysis of quality data across multiple parts, can help to identify larger anomalies that might not be apparent when focusing on singular unit quality test results.

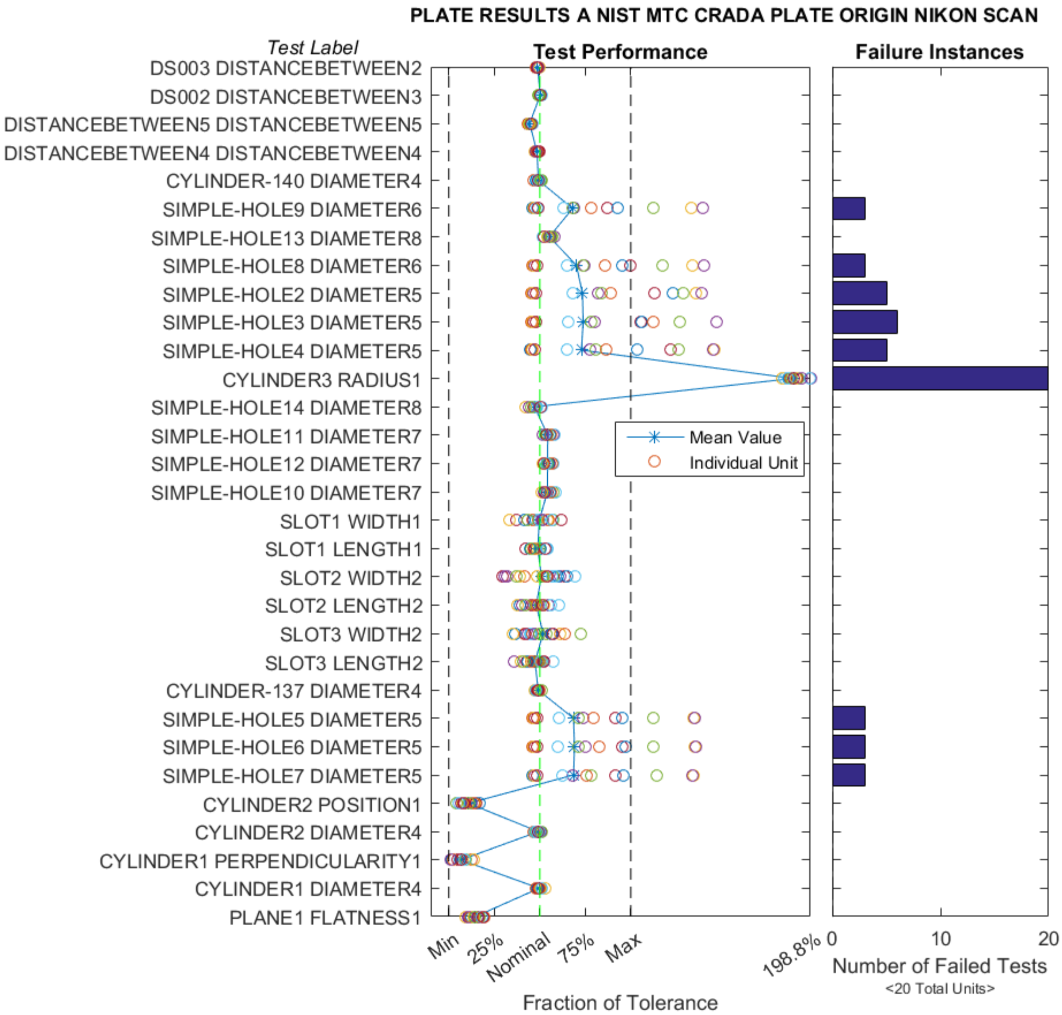

Figure 8. QIF Test Results for Individual Plate Units as Percent of Tolerance Span

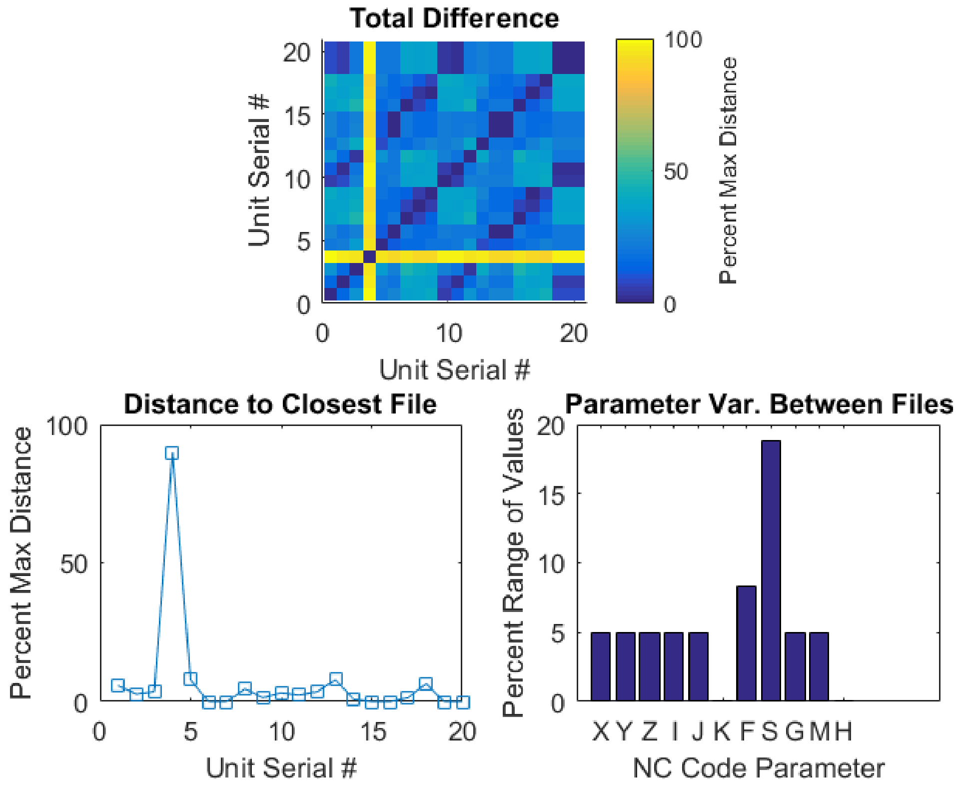

Figure 9. Difference Between Plate Units Input NC-Code Files

4.2. *Machining Parameter Analysis*

For the 20 manufactured Plate units, the machining parameters were varied as prescribed in Table 1. As can be seen in Figure 7, nearly half of the units exhibit a marked increase of the average deviation from nominal in the QIF recorded tests. These deviations can be directly correlated with the machining parameters chosen to direct the production of each unit.

For this analysis, an aggregation of the relative and actual values for these parameters is interpreted directly from the respective NC-Code input files. The exception to this is any reference to "Tool Length," which is not directly recorded in the standard NC-Code file format. Figure 9 shows the calculated differences between the 20 Plate manufacturing input files. Please note that the files for units 7 and 16, as well as those for 6 and 15 are functionally identical. The only notable difference between these plates is the selection of the tool length, which is recorded external to the NC-File. The parameters collected to compare the machining of these parts were those that related to the spatial cutting path of the tool (X, Y, Z, I, J, K), the cutting speed (S), the feed rate (F), as well as preparatory commands and other miscellaneous inputs (G, M, H). Although this work is limited to 11 parameters within the NC-Code, for broader scale operations the analysis could be extended to all possible parameter inputs of NC-Code.

To characterize the relationships between the quality and the input machining parameters for these Plates, explicit interpretations of the input NC-Code is not needed. Instead, characterizations of the various parameter sequences were developed and com-

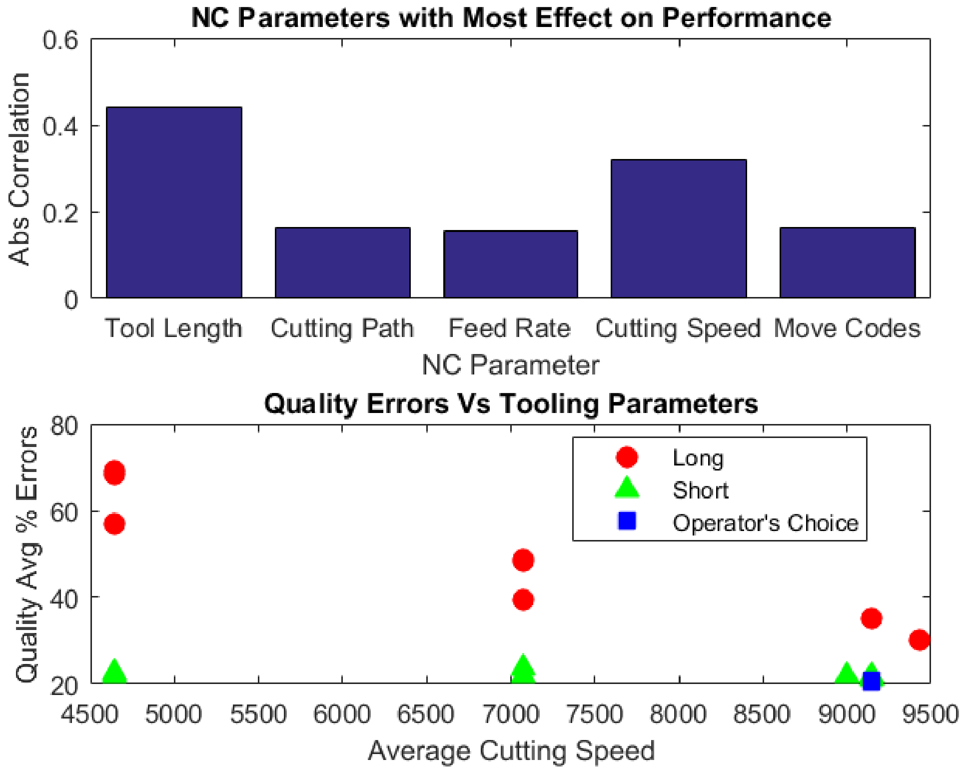

Figure 10. Effect of Machining Parameters on Quality

pared on a relative scale. Ultimately, the selection of this characterization is somewhat arbitrary and matters only in its ability to capture the relative meaningful differences between the files. Towards this end, those parameters relating similar aspects of the machining process have been averaged together to allow a more meaningful interpretation of the results.

When looking for machining parameters that have the biggest effect on the quality of a part, a correlation analysis can quickly reveal strong trends. Figure 10 shows the average correlation between the various selected machining parameters and the recorded quality test results. Based on the upper plot, selection of Tool Length is the most important parameter, closely followed by the Cutting Speed. Somewhat intuitively, but also highlighted by the lower plot of Figure 10, the influence of Cutting Speed on quality is greatly influenced and exacerbated by Tool Length selection. This can be extrapolated to infer that parameter selection is not a one to one influence on the part quality; a confluence of various parameters can have complex end effects on the part quality.

Despite noting that the effects of selecting one parameter may have influence over the effects of others, simple trends can easily be identified in analyses and be used to infer a quasi-optimal set of machining parameters; particularly if more in depth characterization of the NC-Code inputs and variations are made. Even when removing the confounding factor of Tool Length and only focusing on units produced with the Short Tool Length, there is a clear trend of better average quality with increasing Cutting Speed and Feed Rate (see Figure 11). This could be extrapolated such that one might expect even better quality if both were increased beyond the prescribed set

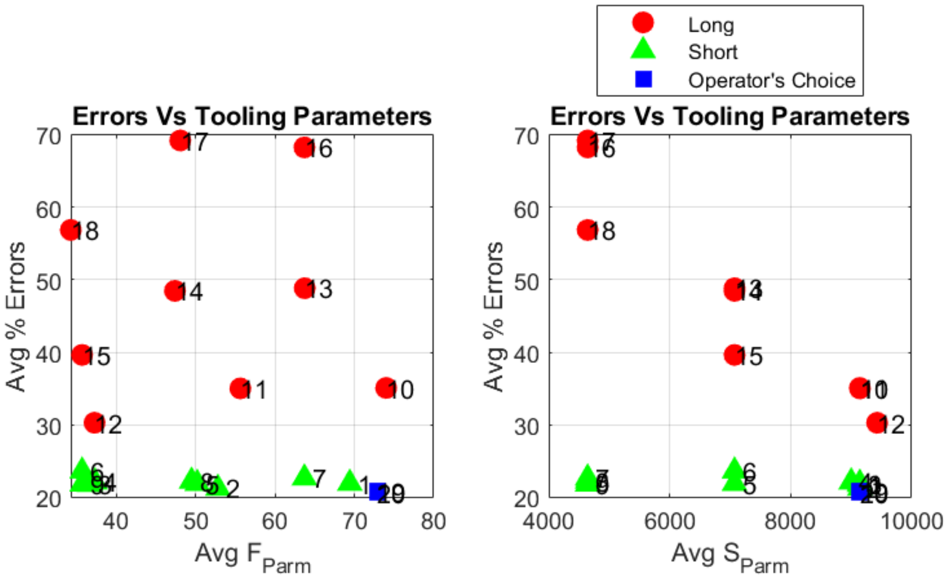

Figure 11. Effect of Speed and Feed Parameters on Quality

of values, and in fact this exactly what is observed with the Operator's Choice' units produced (19 and 20) represented by blue squares in Figure 11.

A full detailing of the correlation to the various QIF tests to the recorded machining parameters is presented in Figure 12. From these results it is clear that the selection of tool length has the biggest effect on the quality of various hole diameters, followed closely by slot lengths. Interestingly, this and other observations made during this analysis were corroborated by the operators who noted that:

- Longer tool lengths caused more vibration thus more chatter on the finish
- Slower RPMs caused chips to gather in flutes of smaller diameter end mills causing swirls on finish
- Parts 16-18, the lower RPMs caused some of the holes to cut oversized due to flexing of small diameter, long length end mills

5. Gaps, Challenges, and Recommendations

Several gaps and challenges were observed during our study. In particular, we were not able to fully automate the data alignment of the CAD (as-designed data), MTConnect (as-executed manufacturing data), and QIF (as-measured / as-inspected data) due to several reasons discussed in this section. However, time savings and knowledge were realized during the analysis of the all the data.

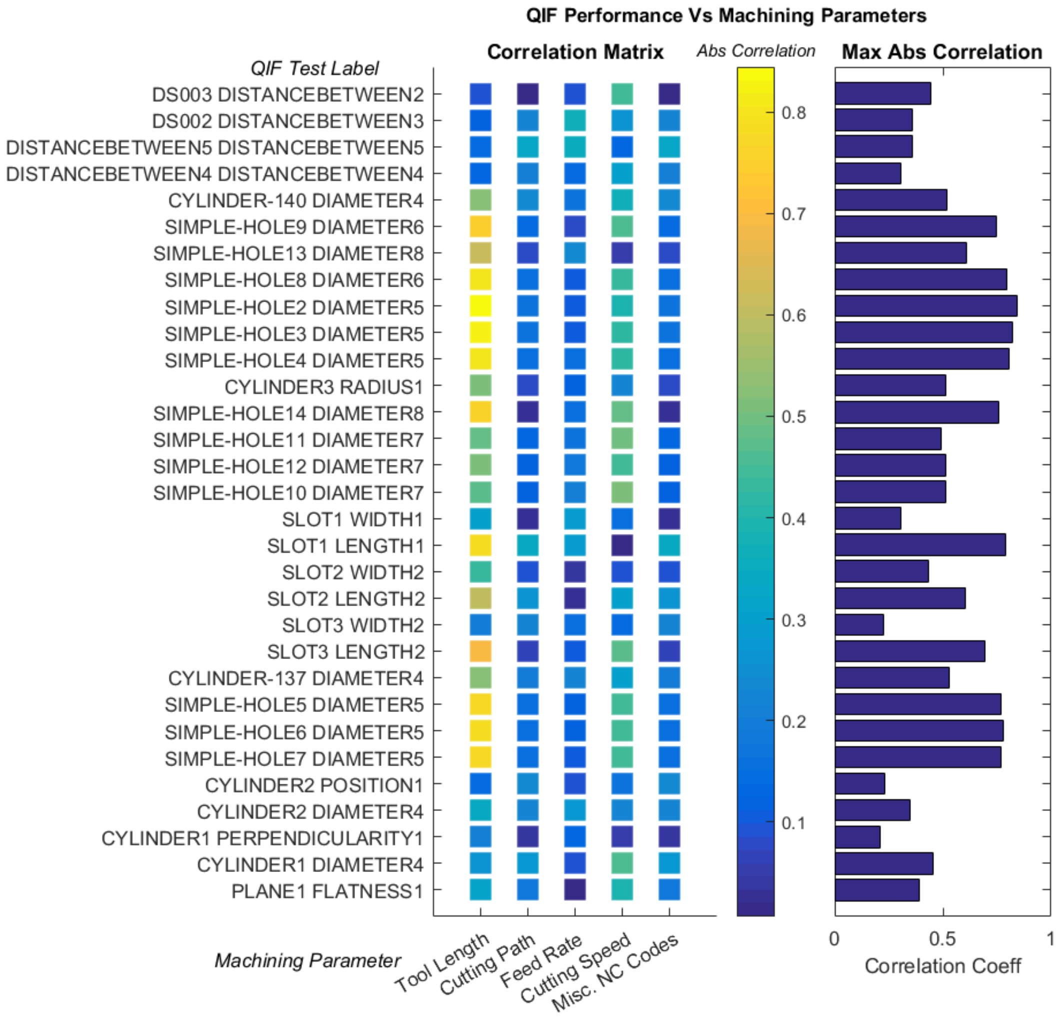

Figure 12. Correlation of Machining Parameters to Individual Quality Tests

5.1. *Gaps and Challenges*

5.1.1. Data Formats

Fischer et al. (2015) and Trainer, Barnard Feeney, and Hedberg Jr (2015) showed that data can be mapped and aligned between data formats available in CAD, CAM, and CAI applications. However, considerable amount of technical experience and time is required to complete the mappings. In addition, we observed that the context or viewpoint of a data element could be different between each of the data formats. For example, a grouping of shape elements are considered a "feature" in the CAD application and data formats for design, but in the metrology data formats, the feature is defined with further context (e.g., hole, slot, pocket). This mismatch between viewpoints makes it difficult to quickly ascertain information and knowledge from aligning data sets retrieved from different phases of the product lifecycle.

Further, we observed that there still remains little to no way to provide feedback to design, even in a model-based environment. The best case is still to use screen-shots with markup and then email them to the design authority. Industry needs a way to directly and efficiently capture feedback within the various data sets and then exchange that information between phases (e.g., design, manufacturing, quality) of the product lifecycle. However, this requires more than application support. The data formats used to exchange data between the phases of the lifecycle must support interoperability of the feedback data. To date, no standards-based data format supports iterative and incremental changes – analogous to "track changes" in a word-processing document – in data for the purpose of feedback. Commercial CAD verification and validation tools are available that provide a "change vector" by analyzing variation between one version of a CAD file and subsequent version. However, this does not provide a clear feedback mechanism for industry. Industry requires an explicit feedback mechanism supported by the various domain-specific standard-based data formats.

5.1.2. Manufacturing Data Collection

The only requirement of an MTConnect implementation is that the device of interest provide the data item `AVAILABILITY`, which indicates the ability of the device to provide data. Because of this requirement, there is no minimum set of data that one may expect from an MTConnect-compliant device. Most implementations of the standard are enabled by a vendor- or third-party-provided Adapter that communicates the native data from the device to the MTConnect Agent. This limits the user to data selected by the Adapter developer, which in turn may be limited by the data exposed by the device controller. Some vendors provide Adapters that provide a full feature set from the device or allow the user to select from a larger set of data items, but these types of Adapters are not commonly available in a wide variety of MTConnect-compliant devices. For example, the three-axis machining center used for this research had a limited set of available data items as shown in Table 4.

Table 4 shows that position is not a data item that is supported by the MTConnect implementation of the machine used in this study. The lack of position data is a critical challenge when attempting to link design, manufacturing, and inspection since linking as-designed, as-planned, as-executed, and as-inspected data is done through the features of a part. Because we did not have position data, we had to integrate the as-executed data by relying on the current block number being executed as reported by our MTConnect implementation (see Section 3 and Figure 4 for more information). This approach allowed us to manually integrate data flows from different lifecycle

Table 4. Data available from Hurco VMX24 machining center

Category	Data Item	Description	Units
Sample	ACCUMULATED_TIME	Program runtime	sec
	ACCUMULATED_TIME	Spindle time	s
	AVAILABILITY	Availability of data	n/a
	PATH_FEEDRATE (ACTUAL)	Actual feedrate	mm/s
	ROTARY_VELOCITY (ACTUAL)	Actual spindle speed	rev/min
Event	EMERGENCY_STOP	Emergency stop status	n/a
	EXECUTION	Program status	n/a
	LINE	Executed block number	n/a
	PART_COUNT (ALL)	# of completed cycles	n/a
	PATH_FEEDRATE_OVERRIDE	Feed override	%
	PATH_FEEDRATE_OVERRIDE (RAPID)	Rapid override	%
	PROGRAM	Name of executed program	n/a
	PROGRAM_EDIT_NAME	Name of edited program	n/a
	ROTARY_VELOCITY_OVERRIDE	Spindle speed override	%
	TOOL_NUMBER	Current tool identifier	%

stages. Future efforts to automate this integration would require the flexibility to obtain additional data items such as position.

Another important challenge when collecting manufacturing data is the inability to control the sampling rate, which is dictated by the Adapter and implementation of the MTConnect standard for the device of interest. For example, the primary responsibility of a machine-tool controller is to manage the machining process. Providing data via an MTConnect Adapter is a secondary concern, which means that the sampling rate may decrease if the controller is executing a more complex toolpath. Similarly, legacy equipment may be limited in its ability to provide data at a reasonable sampling rate because the equipment itself lacks the capability due to age. Okuma provides Adapters that have the flexibility to increase the sampling rate, but this capability requires the user to decrease the number of data items that may be collected. The feasibility of such a trade off would be dependent on the use case of interest.

5.1.3. Data Linking and Analysis

The results of our research show that we were unable to explicitly link feature-to-feature between each data set collected from the different phases of the lifecycle. The root cause for this failure is because there is no persistent identification of features between the standards-based data formats. When we translated the CAD model from the proprietary CAD format to the neutral standards-based STEP AP242 format, the feature identifiers from the CAD system were lost. Further, the MTConnect identifiers are connected to data elements and do not contextualize any features that are linkable semantically back to the CAD data. Lastly, QIF supports a universally unique identifier (UUID) for each data element defined by QIF, but unless the application generating QIF Results uses the same plan, there is no way to generate QIF Results data sets from two different locations and have the same feature and characteristics identifiers between all the data sets.

We were successful in visually linking and aligning the data sets collected during our research. However, all linking was completed manually using significant human input, analysis, and inference. The visualization was helpful to analyze observations from the data, such as how spindle speed and feed rate related to part features during the fabrication process. But, an analyst would generally only want to generate visual analytics if a significant issue arises with the part in manufacturing or quality. Otherwise, the value gained from generating the visualizations are not worth the time and cost it requires to generate the visualizations.

5.2. *Positive Outcomes and Recommendations*

While several gaps and challenges were observed during our research, there were also successes and benefits identified. Specifically, the applicable standards (e.g., MTConnect, QIF) work great within their domain of expertise (e.g., fabrication, inspection). MTConnect provides a rich data dictionary to capture and analyze what is occurring during the execution of machining programs. The streaming MTConnect data not only allows an analyst to determine the status of the machine (e.g., availability, controller mode, level of utilization), but also variation of parameters (e.g., cutting path, spindle speed, feed rate) can be analyzed between part runs, such as dynamic time warping (Helu, Joseph, and Hedberg 2018).

Moreover, QIF also provides a rich data dictionary, but only for metrology applications. QIF enables the ability to define an inspection plan, capture results, and store metrology statistics. Our work and others (Fischer et al. 2015; Trainer, Barnard Feeney, and Hedberg Jr 2015; Morse et al. 2016) have shown that the data covered by QIF can be exchanged quickly and aggregated into commercially available metrology software for further analysis. QIF adoption among metrology solution providers is growing quickly and the standard is stable and mature for capturing and exchanging inspection-related information.

However, the outcome of our research has led to two recommendations to harness further benefits. First, each domain (e.g., fabrication, inspection) needs better aligned adoption of the standards by solution providers. While MTConnect and QIF have seen steady adoption growth, the data elements that each commercial application provides using the two standards' data dictionaries varies from one application to the next. Industry needs the type of data retrievable from applications to be harmonized among the solution providers. One way this could be achieved is through implementer forums. For example, the CAx-IF[2] brings CAD solution providers together to develop recommended practices for implementing ISO 10303 (STEP AP242) standards within data translators and validation tools. We have observed within the STEP community that the CAx-IF accelerates the adoption and implementation of the ISO 10303 application protocols within CAD tools. MTConnect and QIF would benefit from similar organizations and activities.

Second, there is a need for standards harmonization across the domains, particularly in the area of identifying entities (e.g., persistent ID). While we were successful in manually generating visual analytics by overlaying the MTConnect and QIF data with the CAD geometry, we could not automatically align the data in a semantic way. Having persistent identification of entities between each data set would enable the ability to automatically align and data mine the information to develop knowledge about what occurred through the cyber-physical transformation of the product throughout the lifecycle. An example of a persistent ID is a UUID attached to features and characteristics represented in a CAD model. Then, a CAM application could embed the

[2] More information available at https://www.cax-if.org/

UUIDs in the NC program, which could be captured using MTConnect in a similar way as g-code line number. For metrology, the UUIDs for features and characteristics could be stored as using the QIF Persistent Identifiers (QPID) definition in the QIF standard. Having the full chain of persistent identification would enable effective and efficient automated mapping between all the data sets. Manual alignments require significant human capital and an automatic data alignment must be achieved if industry is expected to adopt novel data analytic approaches for generating lifecycle-wide knowledge. Using a UUID as a persistent identifier mapped across multiple data sets could satisfy this requirement.

6. Conclusions

This paper set out to present the activities and results of testing several popular manufacturing standards used in the context of smart manufacturing. We presented a test of the open, consensus-based standards‘ ability to integrate lifecycle stages in a small-scale implementation of MBE. We conducted a design, build, inspect experiment to help inform the understanding and performance of the manufacturing standards. Studying data-mining methods, data-integration techniques, and implementation schemes were some of the goals of our work. However, making significant progress in these goals were not achieved because our data integrations could not leverage automatic data-alignment strategies. The results of our work show that the popular data standards used in industry do not support automatic data alignment. Therefore, we pivoted to providing recommendations to the SDOs for enhancing the standards that we expect would enable automatic data-alignment capabilities. We also expect that once automatic data-alignment capabilities are realized, researchers should then be able to discover methods for implementing and transferring standards-based information integration to practice.

We provided two recommendations to the SDOs. First, industry needs standardization of the data elements available across different implementations of the standards. The SDOs for MTConnect and QIF should consider requiring a select set of data element types, while continuing to make other element types optional. Requiring a set of element types would ensure industry can extract a common baseline of data across all operations. Second, industry needs the standards to provide and/or harmonize the ability to generate persistent identifiers (IDs) of features across data sets to enable monitoring the realization of products as they move through the phases of the entire product lifecycle.

The SDOs may partially address our recommendations by setting up implementer forums where solution providers and industry can come together to generate recommended practices for conforming to the standards. The forums would assist with harmonizing the implementations of each standard between the various solution providers who offer applications using the standards. Addressing the recommendations from our work herein would provide industry with a universal baseline of knowledge extraction and further support interoperability of data across the phases of the product lifecycle.

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Disclosure statement

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Acronyms

2D two-dimensional. 9
3D three-dimensional. 4, 7, 9

ANSI American National Standards Institute. 5
ASME American Society of Mechanical Engineers. 4

CAD computer-aided design. 4, 9–11, 13, 22, 24–26, 31
CAE computer-aided engineering. 4
CAI computer-aided inspection. 4, 24
CAM computer-aided manufacturing. 4, 11, 24, 26
CAx computer-aided technologies. 4
CMM coordinate-measurement machine. 13
CNC computer-numerically controlled. 4, 5, 13, 14
CSV comma-separated value. 13

DMIS Dimensional Measuring Interface Standard. 13
DOE design of experiments. 8, 11, 12, 31

FTC Fully-Toleranced Test Case. 9

GD&T geometric dimensions and tolerances. 4

HTTP Hypertext Transfer Protocol. 5

ID identifier. 27
ISO International Standards Organization. 4

MBD model-based definition. 4, 7, 13
MBE model-based enterprise. 2, 7, 9, 27
MBM model-based manufacturing. 7
MBQ model-based quality. 7
MTC The Manufacturing Technology Centre. 2, 8, 13

NC numerical control. 11, 13, 21, 27
NIST National Institute of Standards and Technology. 2, 8, 9, 13

OEM original equipment manufacturer. 8

PDM product-data management. 4

PMI product and manufacturing information. 9, 11, 13

QIF Quality Information Framework. 2–5, 7–9, 11, 13, 14, 22, 25–27, 31

QPID QIF Persistent Identifier. 27

SDO Standards Development Organization. 3, 27

STEP STandard for the Exchange of Product Model Data. 4, 26

STEP AP242 STandard for the Exchange of Product Model Data Application Protocol 242. 4, 7, 8, 25, 26

UUID universally unique identifier. 25–27

XML Extensible Markup Language. 5, 14

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