Quality information framework – quantifying and minimising uncertainty

Thomas R. Kramer*

Department of Mechanical Engineering,
Catholic University of America, USA
Email: kramert@cua.edu
*Corresponding author

Daniel Campbell

Capvidia,
1700 Post Oak Blvd #600C,
Houston TX, 77056, USA
Email: dc@capvidia.com

Abstract: The quality information framework (QIF) is an ANSI and ISO information standard developed by the Digital Metrology Standards Consortium. When QIF was being developed, one of the aims was to make quality engineers as confident as possible in the data used to assess the quality of manufactured products. With that aim, a set of types of uncertainty about the data used to assess product quality was identified, and provisions of QIF were built to address them. This paper describes how QIF handles both aleatoric and epistemic uncertainties.

Keywords: quality information framework; QIF; standard; uncertainty; digital; information; metrology; XML; schema; model-based definition; MBD; model; design; feature; characteristic.

Reference to this paper should be made as follows: Kramer, T.R. and Campbell, D. (2021) 'Quality information framework – quantifying and minimising uncertainty', *Int. J. Product Lifecycle Management*, Vol. 13, No. 1, pp.6–24.

Biographical notes: Thomas R. Kramer received his PhD in Mathematics from Duke University in 1971. He has been a Research Associate of the Catholic University of America and a guest researcher at the National Institute of Standards and Technology since 1984. He has been a principal QIF developer since 2011.

Daniel Campbell is the Vice President of Model-based Definition at the Capvidia company. Before Capvidia, he was the Principal and Software Director at Metrosage, where he had the primary responsibility for the design and development of the Pundit CMM measurement uncertainty simulation software. He is currently the Chair of the ANSI QIF Working Group, and member of Board of Directors of the Digital Metrology Standards Consortium (DMSC). He holds a Bachelor of Science in Computer Science with a minor in Mathematics from the University of San Francisco, in 2003.

Copyright © 2021 Inderscience Enterprises Ltd.

1 Introduction

Assuring the quality of manufactured products is difficult. The beginning of quality data for manufactured products is determining the dimensional requirements of whether they have the intended size, form, orientation, and location within specified limits. Measurements of size, form, orientation and location, however, always have some level of uncertainty caused by the non-deterministic nature of manufacturing and measurement processes (Morse et al., 2018). As presented in Ríos et al. (2019), that sort of uncertainty may be called aleatoric. Methods for expressing measurement uncertainty resulting from aleatoric causes are well-developed. But uncertainty in manufacturing quality data extends well beyond that into epistemic uncertainty (Ríos et al., 2019) – not being sure of critical facts. Manufacturers who want to make products of known quality must take all types of uncertainty into account.

The Quality Information Framework – an Integrated Model for Manufacturing Quality Information (generally known as QIF) is an information standard that provides for expressing measurement uncertainty and seeks to minimise other uncertainties as well. QIF provides a strong strand in the digital thread by integrating model-based definition (MBD) with measurement planning, measurement results and measurement statistics. In addition, it may be integrated with other digital thread information technologies such as ISO 10303 (STEP) and MTconnect (Helu et al., 2017).

During QIF development, to make quality engineers confident about QIF data, types of uncertainty about quality data were identified, and provisions of QIF were included that address them.

This paper describes QIF briefly in Section 2, describes how QIF handles uncertainties in Section 3 through Section 11, and ends with a conclusions in Section 12.

2 Background

The Digital Metrology Standards Consortium (DMSC) began development of QIF in 2010. Four versions have become American National Standards approved by the American National Standards Institute. The current version is 3.0 (Digital Metrology Standards Consortium, 2018). It is also an ISO standard (Digital Metrology Standards Consortium, 2020). As described in Zhao et al. (2011), QIF fits in a larger world of standards for dimensional metrology that includes metrology plans, metrology results, measurement device control programs and control program execution. QIF also fits in the world of MBD as will be described.

2.1 *The QIF model*

2.1.1 *Overview*

QIF facilitates the interoperability of manufacturing quality data between system software components. Different sorts of data are required at different stages of the manufacturing life cycle. To handle the different stages but keep the data interoperable, QIF includes:

- a document model that covers all manufacturing stages
- six application models for different stages
- a library of supporting models, most of which are used at more than one stage.

As shown in Figure 1, the six application models are:

- QIF MBD
- QIF plans
- QIF resources
- QIF rules
- QIF results
- QIF statistics.

Figure 1 QIF version 3.0 information architecture (see online version for colours)

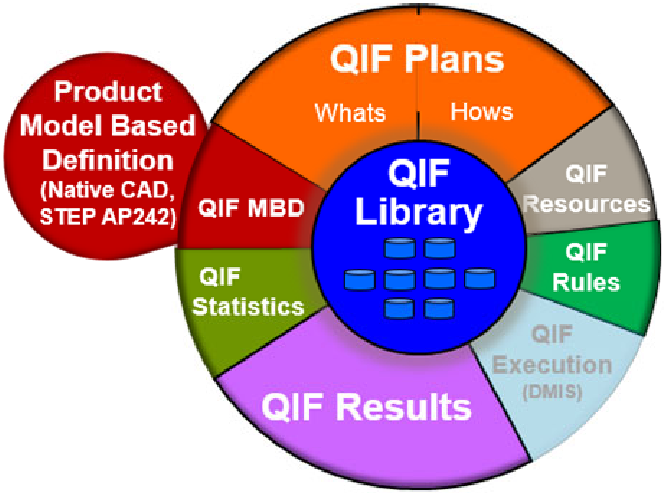
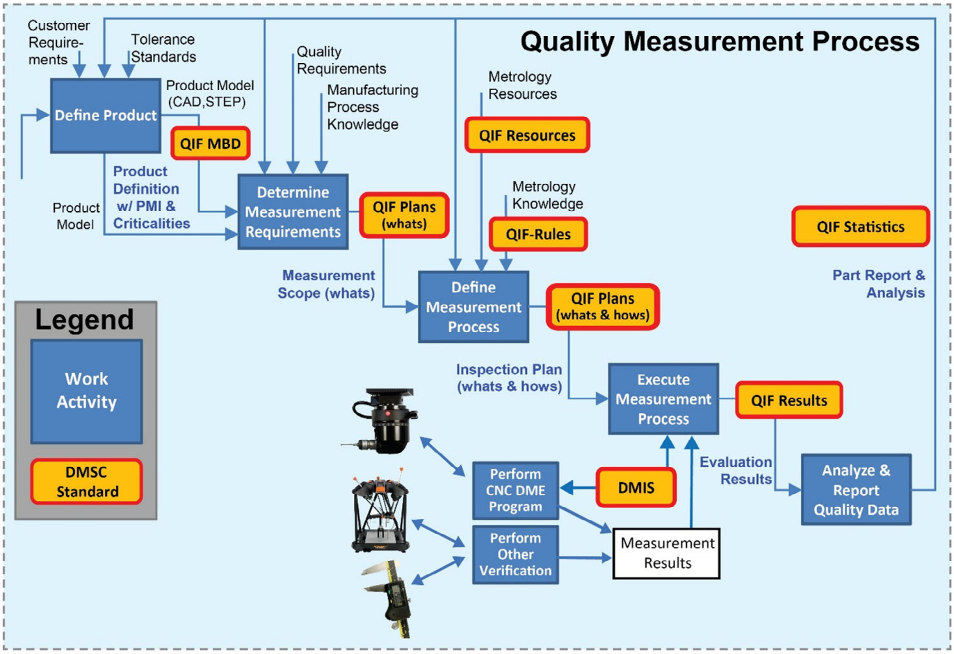


Figure 1 also includes 'Dimensional Measuring Interface Standard (DMIS)' as the QIF execution application. DMIS works with QIF but is not part of QIF. It is a separate standard of the DMSC (Digital Metrology Standards Consortium, 2016).

The model is expressed in a combination of natural language (English), XML Schema Definition Language (XSDL) (W3C, 2004a, 2004b, 2004c), and eXtensible Stylesheet Language Transformations (XSLT) (W3C, 2007). Normative parts of the QIF standard include a 537-page document, 23 XSDL schema files headed by QIFDocument.xsd, and a handful of XSLT files. The schema files (which cover over 100,000 lines) define the structure of QIF XML instance (i.e., data) files and provide many constraints on the data. The XSLT files provide additional constraints on the data that cannot be expressed in XSDL. The text document describes what it all means and how the data is to be interpreted. All of those items plus sample XML instance files may be downloaded free of charge from the DMSC websites (Digital Metrology Standards Consortium, https://qifstandards.org, https://qualityinformationframework.github.io). XML instance files must be used for QIF data and must conform to the QIF schema following the rules for information sets conforming to schemas (W3C, 2004d).

QIF does not require any particular work flow, but the essence of one of the most common QIF work flows is shown in Figure 2.

Figure 2 QIF model-based quality workflow (see online version for colours)



2.1.2 *QIF related to ASME Y14.5 and ISO GPS*

QIF was originally envisioned as a computer-readable version of the ASME Y14.5 standard 'dimensioning and tolerancing' (ASME, 2004a, 2009). Y14.5 defines, among other things:

- features (stereotypical shapes) such as circles, planes and cylinders
- a variety of types of tolerances
  - a size – e.g., length, diameter
  - b form – e.g., straightness, flatness, circularity
  - c orientation – e.g., parallelism, perpendicularity
  - d location
  - e profile
- datums
- datum reference frames.

QIF defines all of these in XSDL with the same meaning they have in Y14.5. QIF, however, divides the Y14.5 notion of tolerance into two parts:

1 characteristics (what sort of thing is being controlled)
2 tolerances (how much the measure of that thing may vary).

As QIF matured, items not in Y14.5 were added to meet the needs of users. Many users prefer to use the ISO equivalent(s) of Y14.5, generally known as ISO geometrical product specifications (GPS). An overview of ISO GPS is provided in ISO (2012) and a complete listing of the several dozen GPS standards is given in ISO (https://www.iso.org/committee/54924/x/catalogue/). ISO GPS items not in Y14.5 have been added to QIF. A group of welding characteristics also exist in QIF. In QIF 3.0, there are 37 types of feature and 73 types of characteristic. Five of the six QIF application areas deal with features and characteristics. The QIF measurement resources area does not; it defines metrology devices.

2.1.3 QIF MBD

The QIF MBD model provides an unambiguous definition of the shape of a solid object. The shape definition can be expressed in a variety of ways:

1 a boundary representation of the sort provided by solid modelling systems and used in CAD packages
2 a triangulation or mesh format
3 point cloud data
4 a hybrid of any of the previous three methods.

In Figure 2, it appears that QIF MBD is used only for planning, but QIF MBD is used also for applications that:

1 generate code for computer-driven inspection devices
2 display results
3 display statistics.

The QIF MBD model also provides a description of assemblies of parts, visualisation of shapes, and visualisation of symbols for characteristics.

The QIF MBD model is similar to the model of Part 242 of the Standard for the Exchange of Product model data (ISO 10303, known as STEP) (ISO, 2020). Unpublished comparisons of the two models have been made, and commercial products such as MBDVidia from Capvidia (https://capvidia.com/products/mbdvidia) exist that will translate MBD models between QIF and STEP Part 242 formats. Work is underway in an ISO Digital Manufacturing Working Group (ISO, https://ap238.org/people) to attempt to define a formal mapping between the two, so that non-commercial translation might be done.

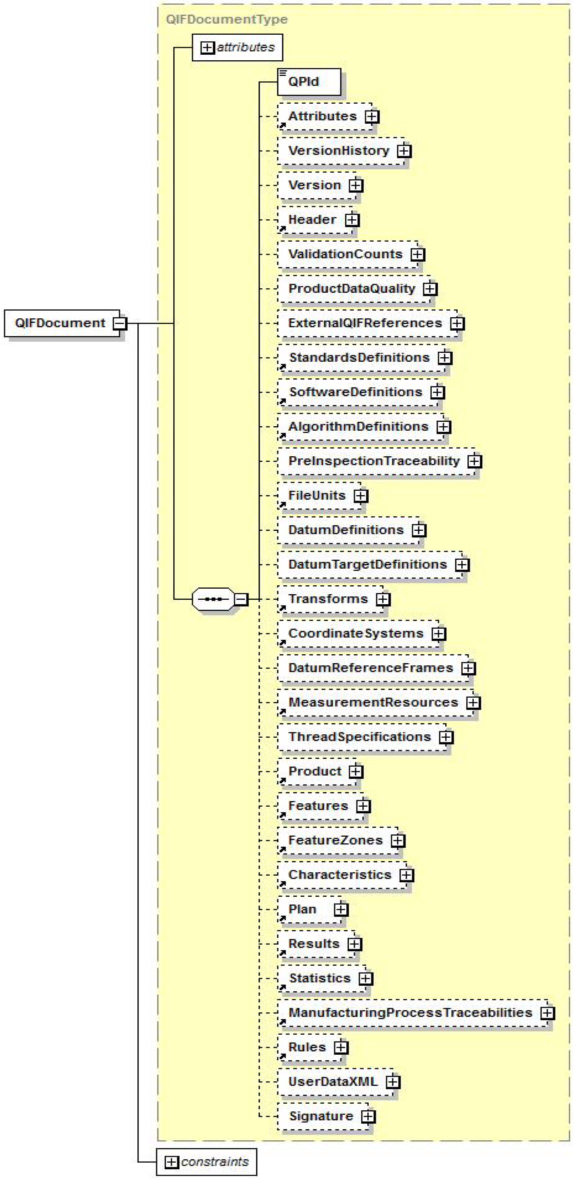
2.1.4 QIF rules

The QIF rules model provides a computer-readable method of specifying metrology rules, such as what pattern of coordinate measuring machine (CMM) touch points to use, what algorithm to use for analysis, or how to select measurement devices. The rules model does not provide a set of rules; it provides only a method of representing rules. As shown in Figure 2, the rules and measurement resources models are used in planning for making measurements.

2.1.5 QIF document

A QIF instance file is a tree structured as specified by the XSDL model. The root of the tree is QIFDocument, which has elements as shown in Figure 3. Each of the elements shown in Figure 3 has elements so that the tree branches, but the branches are not shown in Figure 3.

Figure 3 QIFDocument structure (see online version for colours)



2.1.6 QIF globally unique identifiers

To facilitate reducing uncertainty associated with the risk of collisions of addressing of data, QIF makes extensive use of universally unique identifiers (UUIDs). UUIDs used in QIF are called QPIds and are of type QPIdType, but they conform to the standard for UUIDs (ISO, 2014).

2.2 QIF and uncertainty

Quality engineers want to be as confident as possible in the data used to assess the quality of manufactured products. The following types of uncertainty about the data used to assess product quality, however, can arise:

- uncertainty about the accuracy of nominal values
- uncertainty about measurement units
- quantified measurement uncertainty
- uncertainty about the identity of measurement devices
- uncertainty about the accuracy of measurement devices
- uncertainty whether measurement devices are calibrated
- uncertainty whether measurement devices are used properly
- uncertainty whether measured values were recorded correctly
- uncertainty about product data quality
- uncertainty about data file integrity
- uncertainty about the algorithms used to analyse measurement data
- uncertainty about the software used to analyse measurement data
- uncertainty about the standards that have been used for calibrations, measurements and analyses.

QIF addresses each of these uncertainties as described in the following sections.

3 Uncertainty in nominal values and units

The Units.xsd schema file in QIF provides for specifying continuous nominal numerical values in terms of an xs:decimal. With only a number, it is uncertain how accurate the number is. For most computer applications, when a number is read from a file, regardless of the number of decimal places in the number coming in, by default, the computer stores the number in binary form using a fixed number of bits. The number of bits depends on both:

1. the maximum number for the particular computer (usually 32 or 64)
2. the type of number (e.g., short, long, or int) in the language of the application.

Then, if asked to print the number, the application usually prints the number with either:

1. the maximum number of significant figures corresponding to the number of bits
2. however many decimal places have been specified by the application for printing numbers.

Applications can be programmed to remember the print representation of numbers that are read in and to use that representation when printing the number out, but that is unusual.

To deal with that problem, QIF defines the SpecifiedDecimalType for use in nominal values. An instance of the SpecifiedDecimalType may optionally have one or both of a decimalPlaces attribute and a significantFigures attribute. A SpecifiedDecimalType defines an xs:decimal type with two optional attributes: significantFigures and decimalPlaces. The Units.xsd file describes these as follows:

> "The optional decimalPlaces attribute represents the number of places to the right of the decimal point to which the xs:decimal is specified. The actual number of decimal places used may be greater or less than the decimalPlaces attribute. If the value has more decimal places, the extra ones are meaningless. If the value has fewer decimal places, the missing decimal places are implicitly zero."
>
> "A value of xs:decimal type stored in an XML instance file might not have the same number of decimal places as the original input number."
>
> "The number of decimal places may be truncated because of trailing zeros. For example, a number like 10.000 from a part print might appear in an instance file as <Value>10</Value>."
>
> "The xs:decimal representation of a value may have many extra decimal places because of intrinsic computer limitations in representing floating point numbers. For example, a number like 3.15 might appear in an instance file as 3.14999999999998."
>
> "In both cases the original format of the value can be communicated using the optional decimalPlaces attribute: <Value decimalPlaces = '3'> 10</Value> means 10.000."
>
> "<Value decimalPlaces = '2'> 3.1499999999998</Value> means 3.15. The value is to be rounded to the number of decimal places indicated with the decimalPlaces attribute."
>
> "The optional significantFigures attribute represents the number of significant figures with which the xs:decimal is specified. The actual number of digits may be greater or less than the significantFigures attribute."
>
> "Unlike decimalPlaces, the significantFigures value does not affect the format of a value, but rather its meaning. A value becomes uncertain when the number of significant figures is exceeded. A value of 2.3456789 with 4 significant figures indicates that the real value is uncertain and lies anywhere in the range 2.345000… to 2.345999…"

When a number represents a physical value, it may be uncertain what sort of physical quantity is being represented and what unit for that value is being used. Is it a length, an angle, a temperature, …? If it is a length, is the unit meters, inches, furlongs, …? To deal with these uncertainties, QIF has a different value type for nominal values of each of nine physical quantity type: angle, area, force, length, mass, pressure, speed, temperature and time. QIF also provides user-defined unit for other physical quantity types. Each value type is a specified decimal with an associated unit. The unit name may be specified explicitly using an optional attribute (e.g., angularUnit = 'degrees') or implicitly by the FileUnits section of the instance file, the details of which are out of scope for this paper.

4 Uncertainty in measured values

A proper understanding of a measurand's uncertainty is a key part of any measurement (Baldwin et al., 2017; Helu et al., 2017, Section 5.3.8). The ISO VIM (JCGM, 2008) defines metrological traceability as the "property of a *measurement result* whereby the result can be related to a reference through a documented unbroken chain of *calibrations*, each contributing to the *measurement uncertainty*." The 'unbroken chain of calibrations' usually trace back to National Metrology Institutes (NMIs) such as NIST in the USA, the NPL in the UK, or the PTB in Germany. But eventually at the end of the traceability chain is the measurement itself, and this must also have a stated measurement uncertainty. Uncertainties for a dimensional measurement must be *task-specific*; that is, an uncertainty statement for each measurand on the part, under specific measurement conditions, and with a particular level of confidence. For example: 'the uncertainty of the diameter of this nominally 4 mm pin measured with this specific measurement equipment is 0.028 mm at 95% confidence'.

The ISO GUM [JCGM, JCGM 100 Series – Guides to the Expression of Uncertainty in Measurement (GUM)] defines *expanded uncertainty* as "quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand." QIF allows for the (optional) specification of a pair of values as attributes to the MeasuredDecimalType which allow for the expression of an expanded measurement uncertainty. The first attribute is the meanError, which expresses any mean error (measurement bias) encountered in the measurement. The second attribute is the combinedUncertainty, which is the standard deviation of the Gaussian distribution of possible measurement errors, centred on the mean error. In an ideal situation, the mean error value would be zero, meaning that all measurement bias has been accounted for and compensated. However, in practice, there are always uncompensated measurement biases. By combining the mean error and a coverage factor implied by a multiplier on the standard deviation, one can derive the range of measurements that may be derived within a certain level of confidence. For example, a coverage factor of 2 sigma will obtain an expanded uncertainty at 95% confidence, often referred to as U95.

$$U95 = |meanError| + 2 \times combinedUncertainty.$$

5 Uncertainty regarding measurement methods and devices

An ad hoc approach to the selection of methods and devices used for measurement can lead to a lack of uniformity in result, particularly in a large manufacturing enterprise. This lack of uniformity manifests itself as a source of uncertainty. For this reason, manufacturers often have rules for how product measurements should be made, either by an in-house metrology group or by a supplier. To reduce uncertainty in specifications of what devices to use and how to use them to perform measurements, QIF has a formal model of measurement devices and a formal model of rules. These are in the MeasurementResources and rules elements of QIFDocument, respectively.

5.1 Measurement resources

The MeasurementResources field of QIFDocument provides fields for MeasurementDevice, MeasurementRooms, DetachableSensors, tools and fixtures.

The QIF measurement devices model represents individual devices of 23 different types. A measurement device is defined as a piece of measurement equipment that is directly used by the end user. As an example, a CMM is considered a measurement device, since it is directly manipulated by an end user, but the sensor which is attached to the CMM is not considered a measurement device, since that is an instrument used by the CMM, and only indirectly used by the end user. Each measurement device has a required local id to identify it unambiguously within an instance file (or a set of linked instance files).

Uncertainty about the identity, structure, accuracy, resolution, calibration, and other properties of measurement devices can be minimised by providing a detailed characterisation of these data in the data structures of QIF. For example, a CMM may be any of five derived types (Cartesian CMM, articulated arm CMM, light pen CMM, multiple carriage Cartesian CMM or parallel link CMM). A CartesianCMM has 27 mostly optional fields. That includes name, ModelNumber, SerialNumber, any of four types of resolution, any of five types of working volume and effective working volume, any number of accuracy tests of four types, calibrations, and so on. A more complete knowledge of the measurement tools used for each specific task means lower uncertainties.

5.2 Rules

Any given measurement objective may be carried out using a wide variety of methods. Without a concerted attempt to enforce uniformity in measurement processes, a lack of uniformity can be a significant source of uncertainty in a manufacturing enterprise. QIF addresses this issue with a grammar for specification of algorithmic rules for measurement in the rules model.

The rules in the rules model are of the ‘if these conditions, then these decisions’ variety. The rules model enables writing rules for selecting measurement devices for measuring specific kinds of characteristics on specific kinds of features. It also enables writing rules for selecting the number and pattern of touch points for a feature and for selecting the fitting algorithm to use to fit a feature to measurement points. Each rule may have a UUID. Decisions about measuring devices may say to use them or not to use them. Devices may be indicated not only by their id in the measurement resources but also by class or by model number with or without a serial number.

Logical and arithmetic expressions involving parameters of the features and characteristics may be included in the rules.

It is anticipated that instances of rules will be used in making inspection plans. The rules element of QIFDocument may be assigned a QPId in its version element. A plan may identify the set of rules that was used in formulating it and/or the set of rules that should be used in adding detail to it. In either case, the set of rules is identified by its QPId.

6 Uncertainty in measurement execution

It is normal practice when taking measurements, in addition to recording the results, to keep records about the process of taking measurements. For safety critical products such as aircraft components a great deal of detail is required. See form AS9102B (SAE, 2014), for example. To reduce uncertainty about what should be done and what was done, QIF includes:

- pre-inspection traceability and post-inspection traceability for inspection
- prospective traceability for components in a product
- manufacturing process traceabilities (possibly several) for manufacturing

Including manufacturing process traceability enables linking how a product was manufactured with the results of inspection.

6.1 PreInspection traceability

PreInspectionTraceability is an optional element of QIFDocument. Its type is PreInspectionTraceabilityType which has elements:

- InspectingOrganisation
- CustomerOrganisation
- SupplierCode
- PurchaseOrderNumber
- OrderNumber
- AsmPathIds
- ReportNumber
- InspectionScope
- InspectionMode
- PartialInspection
- NotableEvents
- InspectionSoftwareItems
- InspectionProgram
- SecurityClassification
- PlantLocation
- reference to a QIF plan

- FormalStandardId
- attributes.

FormalStandardId is required. The other elements are all optional.

6.2 Post-inspection traceability

InspectionTraceability is an optional element of the results element of QIFDocument. The results element may contain multiple sets of results, so InspectionTraceability is also an element of MeasurementResults (which is an element of the MeasurementResultsSet element of results) so that it may be associated with a smaller set of results. These other inspection traceabilities are of type InspectionTraceabilityType. That has the same elements as PreInspectionTraceability except that AsmPathIds and FormalStandard are omitted and the following are added:

- InspectionOperator
- ReportPreparer
- ReportPreparationDate
- ReportType
- InspectionStart
- InspectionEnd
- errors
- NotedEvents.

A NotedEvent is simply something that occurred during inspection that is worth remembering and would not be recorded in any other element. A NotedEvent may or may not correspond to a NotableEvent (something not unexpected). If it does, the optional NotableEventId will have a value.

6.3 Traceability for components

A QIF component is an instance of a part or assembly in the design of a product. A component has an optional traceability of type ProductTraceabilityType. This prospective traceability is useful for products that are required to have pre-manufacturing data, such as those reported on form AS9102B. The elements of ProductTraceabilityType, which are all optional, are:

- ReportNumber
- ManufacturingProcessId
- FixtureId
- NotableEventIds
- InspectionSoftwareItems

- InspectionProgram
- MeasurementDeviceIds.

6.4 Manufacturing process traceability

An instance of ManufacturingProcessTraceability has 15 elements. It includes items specific to a single operation such as an OperatorIdentifier and a MachineIdentifier. It also includes AssociatedTraceabilityId to link it to an instance of inspection traceability and PreviousOperationId so that a series of operations may be linked together.

7 Uncertainty in algorithms and software

The software and point cloud evaluation algorithms used to evaluate measurements can be a significant source of uncertainty. The use of different software for common measurements can lead to a lack of uniformity in result, which is a source of measurement uncertainty. An improper point cloud fitting algorithm selection may induce a significant amount of uncompensated bias into a measurement, which is a source of uncertainty. QIF provides for reducing uncertainty regarding the algorithms and/or software used for inspections by allowing them to be identified at several places in an instance file. In some cases, identifying an algorithm is an alternative to identifying software.

7.1 Algorithms

QIFDocument has an AlgorithmDefinitions element in which algorithms used in creating the instance file may be defined. Algorithms in the AlgorithmDefinitions may be referenced in other parts of a QIFDocument by using the local id assigned in the AlgorithmDefinitions.

In addition to algorithms defined in the AlgorithmDefinitions, however, substitute feature algorithms have been deemed important enough that a SubstituteFeatureAlgorithmType has been defined. SubstituteFeatureAlgorithmType is a choice among:

- SubstituteFeatureAlgorithmEnum (one of 15 often-used substitute feature algorithms)
- an id of one of the AlgorithmDefinitions
- a text description of an algorithm.

SubstituteFeatureAlgorithmType is used as the type of the SubstituteFeatureAlgorithm element of both ShapeFeatureNominalBaseType and ShapeFeatureItemBaseType.

SubstituteFeatureAlgorithmType is also used for the algorithms that may be selected in the FeatureRules section of the rules element of QIFDocument.

In addition to the use of an algorithm id in SubstituteFeatureAlgorithmType, an algorithm may be identified by id in the following parts of QIFDocument:

- …/StatisticalStudyResults/…/*XXX*CharacteristicStats/AlgorithmId
- …/StatisticalStudyResults/*XXX*Summary/*YYY*/AlgorithmId.

7.2 Software

QIFDocument has a SoftwareDefinitions element in which all software packages used in creating the instance file are defined. Software packages are referenced in other parts of a QIFDocument by using the local id assigned in the SoftwareDefinitions. Software may be identified by id in the following parts of QIFDocument:

- AlgorithmDefinitions/Algorithm/SoftwareId
- Product/ComponentSet/Component/Traceability/InspectionSoftwareItems (five categories)
- PreinspectionTraceability/InspectionSoftwareItems (five categories)
- …/StatisticalStudyPlan/PreinspectionTraceability/InspectionSoftwareItems (five categories)
- …/StatisticalStudyPlan/SoftwareId
- …/StatisticalStudyResults/SoftwareId
- …/StatisticalStudyResults/*XXX*Summary/*YYY*/SoftwareId
- Results/InspectionTraceability/InspectionSoftwareItems (five categories)
- Results/…/InspectionTraceability/InspectionSoftwareItems (five categories).

The five categories of InspectionSoftwareItems are:

- InspectionProgramGenerationSoftware
- InspectionProgramExecutionSoftware
- AnalysisSoftware
- CADSoftware
- DMESoftware.

8 Uncertainty about product data quality

Digital data users may be uncertain about the quality of the data in a QIF instance file. Measures of product data quality exist that are not controlled by either QIF XSDL constraints or QIF XSLT constraints. For example, Department of Defense Product Data Validation Criteria Worksheet in Appendix C.8 of MIL-STD-31000A lists 60 checks of geometry and topology that might be performed (U.S. Department of Defense, 2013). The list includes such things as ‘large gap between surfaces or patches’ and ‘small radius of curvature’.

To reduce uncertainty about data quality, the ProductDataQuality element of QIFDocument provides for summaries of checks performed and checks approved, a declaration of product data quality, and a listing of the individual checks performed with their results.

9 Uncertainty about data file integrity

Users may be uncertain about the integrity of digital data files. Some types of quality data, such as aircraft component measurement data, may need to be preserved intact for decades. This is important enough that an international consortium of aerospace manufacturers named Long-term Archiving and Retrieval (LOTAR, https://lotar-international.org/lotar-standard) was formed and has issued standards.

An existing digital data file may lose integrity either through intentional modification or because of problems with the way the data is stored and retrieved. QIF includes features designed to deal with both intentional and unintentional change.

Causes of intentional modification need no explanation; there is obvious motivation (money) to improve or degrade quality data.

Unintentional change in digital data may occur less obvious but well-documented ways (Lee et al., 2002; Task Force on Archiving of Digital Information, https://clir.wordpress.clir.org/wp-content/uploads/sites/6/pub63watersgarrett.pdf). The material providing digital storage (tapes, disks, solid state memory, etc.) may degrade spontaneously over time. Applications that can deal with the format of the digital data may become unavailable. The hardware on which an application runs may no longer exist. When data is preserved by copying, the copy process may be unreliable.

To reduce uncertainty about the identification of QIF instance files, every QIF instance file is required to be identified by a UUID in the QPId element of QIFDocument.

To reduce uncertainty that a QIF instance file has not been altered (intentionally or unintentionally) QIF has an optional Signature element with type SignatureType defined in the xmldsig-core-schema.xsd schema file (W3C, https://www.w3.org/TR/2002/REC-xmldsig-core-20020212/xmldsig-core-schema.xsd), which implements data elements in the ISO public-key and attribute certificate frameworks standard (ISO, 2017).

This digital signature's features include a certificate containing:

- signature version
- serial number of the certificate
- algorithm id
- certificate issuer name
- validity period
- certificate subject name
- subject public key information
- optional extensions
- certificate signature.

The certificate signature includes a hash value which can be used to detect unauthorised editing or accidental corruption of the QIF document.

Also to reduce uncertainty that a QIF instance file has not been corrupted, when a data element may be repeated (FeatureNominal, for example), that element is contained in a data structure (FeatureNominals, for example) that is a list of the element plus an *n* attribute that gives the number of elements in the list. That provides a consistency check on the data, since any application that reads QIF instance files can easily count the number of items in the list and check it against *n*. Using *n* for the length occurs in 213 different list types in QIF.

The optional ValidationCounts element of QIFDocument has places for counts of 39 of the most important types of data. Each of the counts is the *n* value of a list.

To reduce uncertainty that in the future software will no longer exist that can deal with QIF files, QIF is based on the well-established and widely used suite of XML technologies.

10 Uncertainty in data provenance

Siloed data occurs when data is available to only one domain of manufacturing, and not accessible to the rest of the enterprise. When this data is brought into another domain, it must be duplicated, which is a significant source of uncertainty. To reduce uncertainty that items such as features and characteristics (which must travel across the entire product lifecycle) can be tracked across the stages of manufacturing shown in Figure 2, QIF provides that features and characteristics, may have a UUID element of QPIdType. The UUID might originate in either a QIF file or a non-QIF file such as a CAD file. Thus, a characteristic or a feature labelled with a UUID when it was created can be tracked all the way through the manufacturing process to QIFResults.

Other QIF items such as a set of results, a set of statistics, or a part, assembly, or component may also be labelled with a UUID of QPIdType.

11 Uncertainty in standards conformance

The use of standards provides greater uniformity in a manufacturing enterprise, which implies lower uncertainties. To this end, a QIFDocument has an optional StandardsDefinitions element in which every standard to be referenced in the file is described and labelled with a local id.

Then, wherever a standard is referenced in some other part of QIF, it is referenced by the id assigned to it in the StandardsDefinitions. The characteristics element of a QIFDocument is required to have a FormalStandardId that identifies a member of the StandardsDefinitions. In other parts of QIFDocument, optional standards references are found in the following places:

- Statistics/StatisticalStudyPlans/StatisticalStudyPlan/StandardId
- Statistics/StatisticalStudiesResults/StatisticalStudyResults/StandardId
- Statistics/…/CharacteristicsStats/CharacteristicStats/StandardId
- SoftwareDefinitions/Software/ReferencedStandardIds/Id

- AlgorithmDefinitions/Algorithm/StandardId
- StandardsDefinitions/Standard/ReferencedStandardsIds/Id.

The last of those exists because standards often reference other standards.

In addition to standards listed in the StandardsDefintions, standards for the accuracy of CMMs are modelled in more detail in measurementResources (ASME, 2008, 2004b).

12 Conclusions

This paper has reviewed the ways in which the QIF provides manufacturing quality data that reduces the uncertainties associated with manufactured products.

While there is no target date for producing the next version of QIF, it may be expected that future versions will be created and will do more to reduce uncertainty.

QIF has a formal process for recording issues and resolving them, https://github.com/QualityInformationFramework/qif-community/issues. These issues should be resolved in the next QIF version.

Because QIF is large and has so many optional formal elements and attributes, different software vendors may implement different subsets of QIF. It remains to be seen whether this will cause interoperability problems. If so, that will be another source of uncertainty to be resolved. QIF also has optional (capital A) Attributes that users may employ for items missing from QIF. It is planned to review the use of Attributes among users to see if the items modelled with Attributes should be added to the formal model in a future QIF version.

A QIF working group looking into adding more non-contact measuring devices (particularly optical digitisers) to the QIF measurement resources model has been formed. Whenever the next version of QIF is formulated, it will almost certainly include adding such devices.

QIF developers have discussed expanding the use of XSDL to enforce constraints.

QIF development groups have discussed expanding QIF to include manufacturing processes, since quality assurance interacts strongly with those processes.

References

ASME (2004a) *ASME Y14.5M-1994 (Reaffirmed 2004), Dimensioning and Tolerancing – Engineering Drawing and Related Documentation Practices*, ASME, sl.

ASME (2004b) *ASME B89.4.22-2004, Methods for Performance Evaluation of Articulated Arm Coordinate Measuring Machines*, ASME, sl.

ASME (2008) *ASME B89.4.10360.2-2008 Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs) – Part 2: CMMs Used for Measuring Linear Dimensions*, ASME, sl.

ASME (2009) *ASME Y14.5-2009 Dimensioning and Tolerancing – Engineering Drawing and Related Documentation Practices*, ASME, sl.

Baldwin, J., Summerhays, K., Campbell, D. and Henke, R. (2007) *Application of Simulation Software to Coordinate Measurement Uncertainty Evaluations*, Vol. 2, Measure, sl.

Capvida, *MBDVidia* [online] https://capvidia.com/products/mbdvidia (accessed 15 November 2020).

Digital Metrology Standards Consortium (2016) *ANSI/DMIS 105.3, Part 1-2016, Dimensional Measuring Interface Standard*, Version 5.3, Digital Metrology Standards Consortium, sl.

Digital Metrology Standards Consortium (2018) *Quality Information Framework (QIF) – An Integrated Model for Manufacturing Quality Information*, Version 3.0, Digital Metrology Standards Consortium, sl.

Digital Metrology Standards Consortium (2020) *ISO 23952: Automation Systems and Integration – Quality Information Framework (QIF) – An Integrated Model for Manufacturing Quality Information*, ISO, sl.

Digital Metrology Standards Consortium [online] https://qualityinformationframework.github.io (accessed 20 July 2020).

Digital Metrology Standards Consortium, *DMSC* [online] https://qifstandards.org (accessed 20 July 2020).

Helu, M., Hedberg, T. and Feeney, B. (2017) 'A reference architecture to integrate heterogeneous manufacturing systems for the digital thread', *CIRP Journal of Manufacturing Science and Technology*, Vol. 19, No. 2017.04, pp.191–195, Elsevier Ltd.

ISO (2012) *ISO 17450-2:2012 Geometrical Product Specifications (GPS) – General concepts – Part 2: Basic Tenets, Specifications, Uncertainties and Ambiguities*, ISO, sl.

ISO (2014) *ISO/IEC 9834-8:2014 Information Technology – Procedures for the Operation of Object Identifier Registration Authorities – Part 8: Generation of Universally Unique Identifiers (UUIDs) and Their Use in Object Identifiers*, ISO, sl.

ISO (2017) *ISO/IEC 9594-8:2017(en) Information Technology – Open Systems Interconnection – The Directory – Part 8: Public-key and Attribute Certificate Frameworks*.

ISO (2020) *ISO 10303-242:2020 Industrial Automation Systems and Integration – Product Data Representation and Exchange – Part 242: Application Protocol: Managed Model-based 3D Engineering*, ISO, sl.

ISO [online] https://www.iso.org/committee/54924/x/catalogue/ (accessed 20 July 2020).

ISO, *ISO TC 184 Automation Systems and Integration SC4 Industrial Data WG15 Digital Manufacturing* [online] https://ap238.org/people (accessed December 2020).

JCGM (2008) *JCGM 200:2008: International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*, JCGM 200:2008, JCGM, sl.

JCGM, *JCGM 100 Series – Guides to the Expression of Uncertainty in Measurement (GUM)*, JCGM 100, JCGM.

Lee, K.H., Slattery, O., Lu, R., Tang, X. and McCrary, V. (2002) 'The state of the art and practice in digital preservation', *Journal of Research of the National Institute of Standards and Technology*, Vol. 107, No. 1, pp.93–106.

LOTAR, *LOTAR Standard* [online] https://lotar-international.org/lotar-standard (accessed 20 July 2020).

Morse, E. et al. (2018) 'Tolerancing: managing uncertainty from conceptual design to final product', *CIRP Annals*, Vol. 67, No. 2, pp.695–717, Elsevier, USA.

Ríos, J. et al. (2019) 'A review, focused on data transfer standards, of the uncertainty representation in the digital twin context', in Fortin, C., Rivest, L., Bernard, A. and Bouras, A. (Eds.): *Product Lifecycle Management in the Digital Twin Era. PLM 2019. IFIP Advances in Information and Communication Technology*, Vol. 565, pp.24–33, Springer, Cham.

SAE (2014) *SAE Aerospace Standard, AS9102B: Aerospace First Article Inspection Requirement*, SAE, sl.

Task Force on Archiving of Digital Information, *Report of the Task Force on Archiving of Digital Information* https://clir.wordpress.clir.org/wp-content/uploads/sites/6/pub63watersgarrett.pdf (accessed 20 July 2020).

U.S. Department of Defense (2013) *MIL-STD-31000A Technical Data Packages*, U.S. Department of Defense, sl.

W3C (2004a) *XML Schema Part 0: Primer Second Edition*, W3C, sl.

W3C (2004b) *XML Schema Part 1: Structures Second Edition, W3C Recommendation*, 28 October W3C, sl.

W3C (2004c) *XML Schema Part 2: Datatypes Second Edition, W3C Recommendation*, 28 October, W3C, sl.

W3C (2004d) *XML Information Set (Second Edition) W3C Recommendation*, 4 February, W3C, sl.

W3C (2007) *XSL Transformations (XSLT) Version 2.0, W3C Recommendation*, 23 January, W3C.

W3C, *Schema for XML Signatures* [online] https://www.w3.org/TR/2002/REC-xmldsig-core-20020212/xmldsig-core-schema.xsd (accessed 20 July 2020).

Zhao, Y., Brown, R., Kramer, T. and Xu, X. (2011) *Information Modeling for Interoperable Dimensional Metrology*, Springer, London Dordrecht Heidelberg, New York, ISBN: 978-1-4471-2167-1.