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Research Paper

Closing gaps in the digital thread with the Quality Information Framework (QIF) standard for a seamless geometry assurance process

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ABSTRACT

An essential premise for a reliable variation simulation is that information on the geometrical part variations and their accumulation and propagation within an assembly is available, accessible, interchangeable, and usable in all geometry-related downstream activities. For this reason, this article studies the potential of the QIF (Quality Information Framework) standard. It illustrates how it can be used in the sense of Model-Based Definition to close gaps in the digital geometry assurance process. Besides benefits in the automation of variation simulation, it demonstrates that the semantic, feature-based linkage between product specification and inspection information in QIF 3.0 facilitates the augmentation of variation simulation with more detailed feature information for pre-production applications and feeding the digital twin to assure and optimize product quality in the production phase.

1. Introduction

A significant number of quality issues in technical products have their roots in the deviation of part geometry caused by manufacturing and assembly uncertainties [1]. Hence, the individual part features differ from their nominal geometry in terms of size, location, orientation, and form, and their variations accumulate and propagate in assemblies and finally result in diminished product functionality and aesthetics [1,2]. Reducing manufacturing and assembly imperfections to zero is, however, technically impossible [3] – variation is ubiquitous and given by nature [4]. Rather, tolerances are used to manage and limit variability while exploiting technical and economic margins [1]. Therefore, design engineers rely on established and standardized tolerancing systems to communicate the design intent [1], mainly the Geometrical and Dimensional Tolerancing (GD&T) system provided by the American Society of Mechanical Engineers (ASME) and the Geometrical Product Specification (GPS) system provided by the International Organization for Standardization (ISO).[1]

Using these specifications as a starting point, Computer-Aided Tolerancing (CAT) tools help to virtually assure and optimize product quality over the different product development stages [1]. The increasing digitization of production leads to a more seamless link and flow of information between all product life cycle activities and stages, uncovering previously hidden potentials for CAT [5,6]. Consequently, there is an increasing trend towards computerization and automation of the geometry assurance process using model-based and data-driven simulation and optimization routines [6,7].

1.1. Variation simulation and geometry assurance

The main goal of variation simulation is to virtually represent the product behavior while considering variations on both part and assembly levels to predict its quality using Key Characteristics (KC) [1]. Hence, variation simulation uses *geometrical models* to represent the manufacturing-induced part features' variations and *behavior models* to predict the assembly response to the part variations mapping the assembly process and its variability [8]. In literature, various geometrical models have been proposed over the years [9], differing in their type and level of abstraction [10]. Examples include vector loops, matrix models, parametric feature models, mesh-based and point-based representations [9,10]. Since the propagation of the variations, as well as the assembly behavior, is often highly non-linear and cannot be explicitly expressed in a mathematically closed form, numerical simulation approaches are commonly used [8,11]. For the evaluation of geometrical KCs, point- and feature-based models have thus become established and are the basis of CAT software commonly used in industry, such

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[1] In this article, the term GD&T is used without intending that the ISO standardization is less capable.

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as 3DCS®, CETOL 6σ®, Siemens Teamcenter Variation Analysis® or RD&T® [1,9,10].

In this context, the geometry assurance process can be understood as a closed loop of various geometry-related activities applied in the concept, pre-production, and production stages to minimize the effects of variations [2]. The activities differ in their scope for action (part level vs. assembly level), focus (product design vs. process design), and design variables (tolerances, datums/locators, joining sequences, etc.). However, they have in common that they typically use variation simulation models to virtually represent real production scenarios and their effects on the product quality [2].

The lack of detailed information, especially in the design phase, usually calls for assumptions, estimations, and referring to historical data in simulation [7]. Under the vision of Industry 4.0, the industrial production environment is becoming increasingly digitally connected [5]. Sensors and in-line measuring equipment provide a large amount of data, which can be used as input for the variation simulation and to set up digital twins for geometry assurance [7,12]. This digital transformation lets real-time optimization strategies, such as adaptive (re-)manufacturing, selective/individual assembly, or individualized fixture layouts and joining sequences [7], become realistic tools for an effective geometry assurance process.

1.2. Sharing geometry assurance-related information

A seamless transfer and flow of data and information must be guaranteed to ensure that it can be used within the geometry assurance loop [13]. Hence, all software tools must be able to communicate and interoperate with each other [6]. Therefore, a significant share of related works focus on how to share the relevant tolerancing information. Based on either established languages, such as XML, UML, EXPRESS, and OWL, or specially developed languages, for instance, GeoSpelling, the developed tolerance information models aim to describe design, production, and inspection information within one model [14]. Global concepts and frameworks supplement these research activities for controlling the flow of geometry assurance-related data and information [6,13,15,16]. The related works jointly contribute to the vision of a thorough digital thread "linking all systems, processes, virtual and physical data" throughout the entire life cycle via a data-driven architecture and serving as the essential infrastructure for digital twin applications [17].

Model-Based Definition (MBD) is an essential strategy in the digital thread to link the Product and Manufacturing Information (PMI) to 3D digital product models, which are generated in the design phase in Computer-Aided Design (CAD) systems and serve as authority models [18,19]. The main benefits of MBD for CAT can be seen in the automation of certain modeling steps for variation simulation and enriching simulation with manufacturing and inspection data [20]. The information is therefore communicated directly between the different applications within the same software landscape [21,22] or via CAD files in native and neutral formats [23–25]. The STEP AP242 (ISO 10303-242), JT (ISO 14306:2017), and QIF (ISO 23952:2020) standards enable the exchange of model-based product information while guaranteeing systems' interoperability [20]. In literature, STEP AP242 is preferably used as direct input [23,24,26], or to first feed knowledge bases for subsequent activities [25,27,28]. JT is less frequently used in this context but is, for example, a common way to transfer GD&T information from CAD to Siemens Teamcenter Variation Analysis® [24]. Lately, QIF 3.0 is first recognized as a potential solution to map the "as-inspected/as-measured" status of parts [25,29] and to bring information from tolerance verification, primarily measurement results, into CAT [6,20]. In addition to the representation of the product geometry with its specifications, QIF 3.0 supports the information flowing to and from inspection [30], which is essential when integrating manufacturing information into variation simulation.

1.3. Scope of the paper

Although information modeling for tolerancing has intensively been studied in the past research and various solutions have been presented, there is still an ongoing research need in this field [6]. As a result of the increasing digitalization of the geometry assurance process reacting to the industry 4.0 movement, an increasing number of computer tools are involved in controlling and optimally handling the effects of geometrical variations [6]. However, sharing the relevant information between the software systems used in design-, manufacturing-, and inspection-related activities is hampered by missing information infrastructures and interfaces [6]. In practice, information is still exchanged using multiple non-standardized and unlinked data formats and relying on strategies that are unsuitable for automation, such as 2D drawings or unstructured lists of measurement information, forcing to manually extract and transfer the provided information to the respective systems [5,6]. It is still common to manually transfer specification and measurement information within the CAT environment to set up the geometrical and behavior model for variation simulation. The consequences are inconsistent information and decoupled, non-updated models [31], complicating the collaboration between the actors involved, leading to errors and requiring manual intervention [5]. Thus, significant gaps in the digital thread for geometry assurance still exist.

MBD has turned out to be an important element for closing these gaps in the information flow [5,31]. It offers a standardized and mutual base to gather information in one common data file and functions as a neutral interface for exchanging information between the software systems embedded in the geometry assurance process. The related works, presented in Section 1.2, indicate that MBD has already found its way into CAT environments. Semantically linking assembly structure, part feature, and GD&T information helps communicate products' "as-designed" status to variation simulation-based downstream activities. The exchange of product specification information through STEP AP242 is mainly sufficient to automate variation simulation for tolerance analysis and synthesis in the design stage. Despite its importance for geometry assurance based on digital twins, a model-based exchange of the "as-inspected" status of parts has not yet been studied. According to [31], the industry sees the lack of a central, continuously updated digital model throughout the entire product development process as the main hurdle for the practical implementation of digital twin-based geometry assurance activities. Integrating manufacturing information is a key element in variation simulation to represent given manufacturing conditions and to make meaningful decisions in the geometry assurance process [6]. QIF 3.0 is per se designed to share specification and verification information between the various computer-aided systems for design, tolerancing, and inspection. So far, however, it has primarily been considered for inspection-related downstream activities, e.g., in [32], and has not been studied in detail to augment variation simulation with measurement information and directly feed the digital twin. In comparison to STEP AP242 and JT, QIF 3.0 has its roots in the measurement and quality assurance domain, following the aim to combine the relevant information in a common information container [30]. Thus, QIF 3.0, by its global motivation, principally bears great potential to provide a solution for a seamless information flow for geometry assurance. Hence, this article examines the research question of *how QIF 3.0 can be used to create a digital thread for variation simulation-based geometry assurance*. The novelty of this article lies in a comprehensive study on the potentials and shortcomings of QIF 3.0 to serve the individual needs of an MBD-based geometry assurance process. Solution approaches for semantically mapping specification and verification information from QIF 3.0 on models for variation simulation are introduced, exemplarily applied to a case study, and critically discussed. The article is structured as follows. Section 2 introduces the structure and main benefits of QIF 3.0. This information serves as the basis to present the potentials of QIF 3.0 to support variation simulation-based geometry assurance activities in

Section 3. A discussion on the challenges of implementing QIF 3.0 in the geometry assurance process and future prospects follows in Section 4, before Section 5 concludes the article with a summary and an outlook on future research activities.

2. QIF 3.0 – general structure and benefits

Before discussing the potential of QIF 3.0 for variation simulation in more detail and presenting different ways for its exploitation, the general structure and content of QIF 3.0 are first reviewed in the following.

2.1. Overview

The Digital Metrology Standards Consortium (DMSC) is responsible for the QIF standard [30,33], which is currently in version 3.0, with 4.0 under development [34]. DMSC is historically known for the development of the DMIS (Dimensional Metrology Interface Standard) specification that provides a neutral "programming language" and reporting format for CMMs [35]. The popularity of DMIS motivated the DMSC to investigate standardizing the interface between each of the steps of the quality lifecycle, including design, measurement planning, measurement execution, reporting, and statistics [36].

The QIF 3.0 standard is made up of a series of XML Schema Definitions, which are templates describing how data are formatted and named as they are carried throughout the quality ecosystem [30, 37]. Files that follow these schema definition templates are formatted as XML documents, which are both human-readable and machine-interpretable [30]. To make the definitions more usable, the schema definitions within QIF 3.0 are divided into different application areas, as shown in Fig. 1, and are supported by a common set of fundamental libraries [30].

Having all of the quality information in a unified format enables myriad down- and upstream applications [37], which by themselves are not challenging but where the gathering and synthesis of data can impede the application. Among these applications are measuring systems analysis (MSA), where having all data in an accessible format allows easy application, and long term archival and retrieval (LOTAR) for data where the original source data may come from a variety of equipment [30].

While QIF 3.0 and STEP AP242 overlap in the MBD representation, QIF 3.0 is capable of capturing both the "as-designed" and "as-inspected" status in one file [25] (see Fig. 1). It puts verification data into a context and semantically links it to the "as-designed status" of the parts described by a set of Boundary Representation (BREP) features [30]. These features carry their geometrical deviations but also propagate them across the parts within the assembly [38].

2.2. Identification designators as links between the "as-designed" and "as-inspected" status

The following section aims to highlight the relevant information on the structure and contents of QIF 3.0, given in detail in the ISO 23952: 2020 standard [30] and its associated HTML-based schema browser [39].

The <QIFDocument> is the highest-level *element* storing all instance files, written in the XML Schema Definition Language (XSDL), and containing several, but not necessarily all QIF information models from Fig. 1 [30]. An *element* represents several pieces of information by further required and optional *elements* and *attributes*. The QIF 3.0 structure is based on a decoupled normalized relationship model [30]. The main idea behind this structure is that unique identification designators (id) create the relationships between the individual local objects, i.e., the grouping of information defined by QIF 3.0 elements, which avoid recalling the entire data [30]. The decoupling principle allows components to be reused since the child and parent elements are not

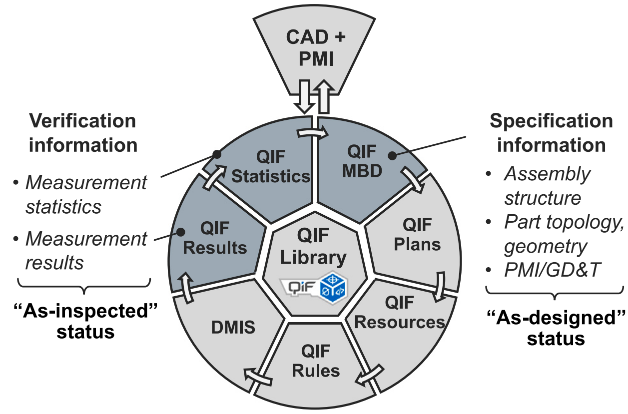

Fig. 1. Overview on the QIF. 3.0 information structure, as given in [30], with highlighted elements relevant for variation simulation.

directly coupled, which is beneficial to keep file sizes low [30]. This concept further allows persistent referencing to external files through QIF Persistent Identifiers (QPIds), an implementation of a Universally Unique Identifier (UUID) [30].

The <Product> element contains all information about the parts and assemblies, usually originating from a native CAD model. An assembly is defined by several <Component> elements, referencing the <Part> and <Transform> elements, giving information on the virtual part and its position (see Fig. A.1 for more details). In line with the Boundary Representation (BREP) method, a part is described via a <TopologySet>, i.e., the "relationships between the geometric units" [30] and a <GeometrySet>, i.e., the "shape of the model elements" [30]. Fig. 2 shows an example of the QIF 3.0 representation of a cuboid-shaped part with two holes.

Each <Body> is defined by a <Shell> with a set of <Faces>, which in turn consist of a <Surface> element and one or several outer and inner <Loop> elements defining the face's boundaries. Each <Loop> is characterized by multiple <CoEdge> elements, which are further specified in the respective <Edge> through the geometry of the curve connecting the edge's beginning and end vertices (see Fig. 2) [39]. The geometry of the 3D surface is clearly defined in the respective <*Surface23> element [39]. The prefix '*' indicates that it is a substitution group with several different substitutes for individual shapes, e.g., a <Plane23> or a <Cylinder23> [39]. The model-based GD&T specification information, directly assigned to CAD features, is presented and represented in QIF 3.0 to make it human-readable and computer-interpretable [30]. QIF 3.0 represents them by <Features> and <Characteristics> elements [30] (see Fig. 3 (top)).

Features are expressed by a set of general <*FeatureDefinition> elements, defining, for instance, the type and size, and serving as a reference for one or more <FeatureNominal> elements [30]. The latter is used to uniquely specify a particular instance of a feature by additional information, such as the location of the feature's axis. This concept is essential in QIF 3.0 to avoid data redundancy [30].

In Fig. 3 (top), both cylindrical holes can be represented by two individual nominal <FeatureNominals> elements with different axis information; however, referring to the same <*FeatureDefinition> element with the shared information on the cylinder's <Length> and <Diameter>.

The <EntityInternalIds> element links the <FeatureNominals> to the respective internal element in the <TopologySet> [30]. The <*CharacteristicNominal> element contains all the tolerance callout information for the directly linked <FeatureNominal> [30]. It is further defined by information given in the <*CharacteristicsDefinition> element, including the tolerance type, value, and zone, modifiers, etc [30].

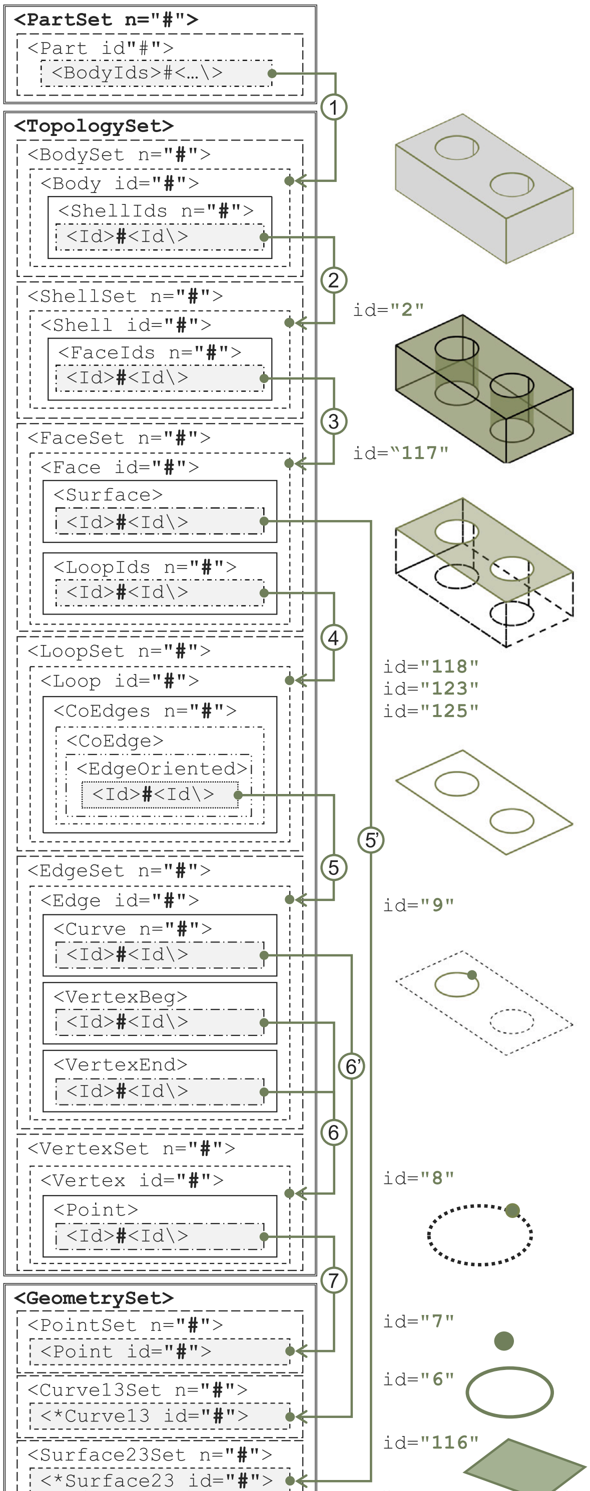

Fig. 2. General structure of QIF 3.0 to systematically represent part topology and geometry.

The information can be shared within multiple <*CharacteristicNominal> elements [30]. Location and orientation tolerances further reference to a <DatumReferenceFrame> element as a set of <Datums>, which in turn reference back to <Feature> elements (see position tolerance in Fig. 3 (top)).

In addition to communicating the GD&T specification, QIF 3.0 features and characteristics are used to represent inspection information, summarized in the high-level <Results> element in different ways (see Fig. 3 (bottom)). When evaluating characteristics, <*CharacteristicMeasurement> elements are used to capture the measured value for a physical instance and its reference to a <CharacteristicItem>, further establishing the link to the specified <Characteristic> [30]. In comparison, a <*FeatureMeasurement> element provides all information on a directly measured or reconstructed feature as well as the reference on the ideal feature specified by the <FeatureNominal>, using the indirect route of the <FeatureItem> element [30]. It additionally offers the potential to carry the information on the underlying inspection points within a <MeasuredPointSet> [30].

If there are multiple measurements for physical instances, the results can be concatenated as individual elements [30]. Alternatively, the <Statistics> element can be used to carry processed statistical information about the observed variations (see Fig. 3 (bottom)), e.g., by mean, standard deviation-, or C_{pk}-values [30]. Hence, both geometrical deviation and variation information can be represented in a model-based way. The term “geometrical deviation” describes the deviation from the nominal shape observed for a single-part instance. In contrast, geometrical variation refers to the variation of deviations observed for a set of different parts manufactured in the same process [40]. The specified features and characteristics semantically couple the nominal, “as-designed” status with the actual, “as-inspected” status captured for one or more part instances. Optional <ActualComponent> elements can further reference the digital representation to its physical counterpart characterized through a <SerialNumber> [30].

3. Exploiting the potential of QIF 3.0 for variation simulation-based geometry assurance

The strengths of QIF 3.0, emphasized in Section 2, offer the potential to set up a digital thread in the geometry assurance process. The idea presented in the following is to harvest the linked information models in different stages in the geometry assurance process, providing a solid ground for the related activities using variation simulation. The “as-designed” status of the product, defined by its nominal geometry and a set of semantic GD&T annotations, forms the starting point and basis for the subsequent downstream activities.

There is typically little or no information on the actual geometrical variations in the early design stages. In the so-called *prediction stage* [41], the QIF 3.0 MBD application data can be used to automate simulation for making statistical predictions on the final product quality (see Fig. 4). As literature and commercial software solutions prove, JT and STEP AP 242 are established alternatives for semi-automated variation simulation modeling. However, using QIF 3.0 will ensure the consistency of the model for later phases.

As soon as first observations by inspection (or virtual manufacturing simulations) are made, more precise statements about the part variations are possible using the verification information carried within the QIF Results and Statistics information model (see Section 2.2). The persistent links to the feature information in QIF 3.0 are beneficial, creating a seamless link between inspection and variation simulation and establishing the digital thread for geometry assurance. In these *observation stages* [41], it depends on whether statistical conclusions about the total quantity are drawn or individualized predictions and optimization through digital twins are made (see Fig. 4).

Regardless of the respective stage, the information represented in QIF 3.0 must be interpreted and mapped to the models used in the respective CAT tool [20]. The mapping strategy primarily depends on how the nominal and deviation-related status of the part geometries are represented in variation simulation (see Fig. 5). As highlighted in Section 1.1, various geometrical models exist, differing in computational efficiency and level of detail. Fig. 5 (center) contrasts three common models with different information content for explanatory purposes. Vector models reduce the 3D feature information to a finite list of parameters to describe the location of a representative point

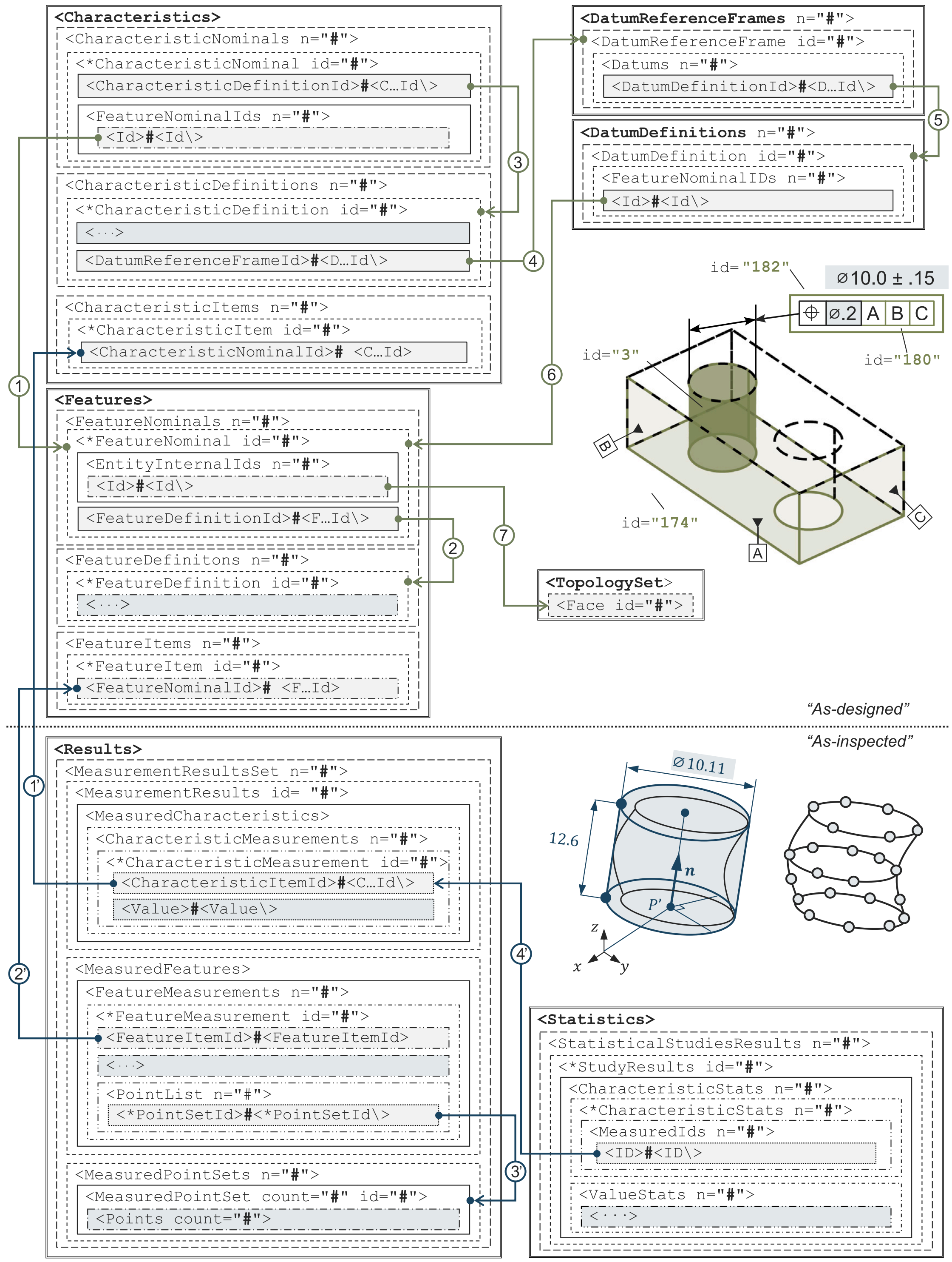

Fig. 3. General structure of QIF 3.0 to systematically represent the GD&T specification information (top) and verification information (bottom), semantically linked to a part's <Topology>.

within the whole tolerance chain [42]. Feature-based models use geometric standard primitives to represent the non-nominal status via their characteristics, translations, and rotations in 3D [43]. Although these models follow a feature-based approach with feature definitions similar to those used in QIF 3.0, they differ in detail to parametrically describe surfaces. Point-based models represent a feature's surface via a set of discrete points, which in mesh-based models additionally serve as nodes triangulating the surface, thus describing its shape locally in more detail than parametric features [41]. Consequently, depending on the chosen geometrical model type, it is necessary to translate the QIF 3.0 information, including additional information reduction or expansion operations. This also applies to the measurement information carried in QIF 3.0, which, as shown in Section 2.2, is available in the form of single characteristic values, measured features or measurement points (see Fig. 5 (bottom)). Fig. 5 generally exemplifies the need for mapping the "as-designed" and "as-inspected" information to three geometrical models but does not aim to give recommendations for choosing a geometrical model for the product and verification information carried in QIF 3.0.

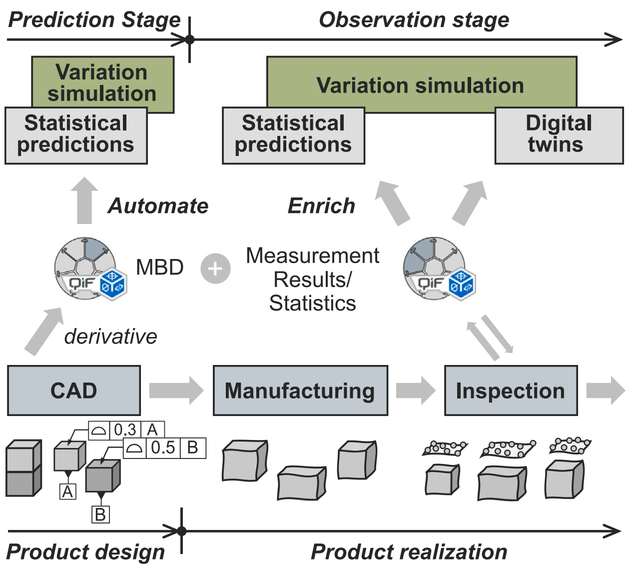

Fig. 4. General potentials of QIF 3.0 in the digital quality assurance process.

The presented potentials of QIF 3.0 to enhance variation simulation in the prediction and observation stages are first studied in more detail in the subsequent Sections 3.1–3.2, before Section 4.1 focuses on its challenges and prospects. Though there are different strategies to perform variation simulation, the following focuses on QIF 3.0 for variation simulation based on triangulated surface models. Mesh-based representation models show their strengths in realistically modeling geometric shape deviations [41] and non-rigid parts [1,44] and are the basis of well-established variation simulation approaches in theory and practice. However, it must be understood as one example of a representation model illustrating how information carried in QIF 3.0 can be harvested and used within the geometry assurance process in the following.

3.1. Automation of mesh-based variation simulation through specification information

Variation simulation consists of three main components: a geometrical model to represent the part geometries and their variations, a behavior model to model the propagation of the variations within an assembly and the probabilistic assembly response, and an evaluation technique to estimate and assess the influence of the variations on product quality [8].

The first step is to set up the geometrical model. Instead of manually extracting the information from drawings or CAD models and transferring it to the geometrical model, the information linked in QIF 3.0 can be used to automatically define the geometrical model. Mesh-based models are characterized by a discrete local geometry representation via points and triangles. Thus, the information described via topology and geometry from QIF 3.0 must be translated into a discrete description (see Figs. 2 and 5). Since the individual faces are mathematically unambiguously described, a step-by-step discretization of the surface by generating surface point grids and a subsequent tessellation would be conceivable – insofar as edge points shared between features are harmonized. Alternatively, pre-existing triangulated surface models can also be used as the basis for a feature-based description. This approach is more general, as it does not require the development and implementation of meshing strategies since it can directly use any meshes generated for the respective application purpose in third-party tools, such as in CAT tools for rigid and non-rigid variation analysis (see Fig. 6 (left)).

However, a strategy to morph the information from QIF 3.0 on the respective portions in the discrete surface mesh is then required. Following ISO 17450-1:2011 [45], the strategy must include a partition operation to decompose the surface mesh and an association operation to assign the partitioned mesh portions to the features. Applying partition and association operations to the generated surface mesh is less complicated than measured, non-ideal geometries. The shape is approximated by discretization but is ideal, and the features are already known from QIF 3.0. Similar to automated routines based on STEP AP242 [23], using the QIF 3.0 feature definitions overcomes the shortcomings of manual mesh partition approaches [46]. In contrast to other existing automated mesh segmentation methods [47], there is no need to recognize the feature type and identify its intrinsic characteristics [45]. The feature definition and thus the link to other elements, such as the <Characteristics> and <Features>, is preserved.

Fig. 6 (center) illustrates the principle of an automated morphing strategy, including partition and association of QIF 3.0 features on mesh-based geometrical models. The aim is, therefore, to find subsets within the set of triangles $\mathcal{T}$ that represent the individual QIF 3.0 features. The triangle subsets $\mathcal{T}_i$ are, in turn, characterized as subsets of the total point set $\mathcal{P}$, where three vertices $\{P_j, P_k, P_l\}, j \neq k \neq l$ represent one triangle $\mathcal{S}_q$. Thus, each surface point P_i can be associated with at least one triangle subset $\mathcal{T}_i$. Hence, to form $\mathcal{T}_i$, the triangles must be identified via the points, which lie on the surface of a feature, which is mathematically exactly described within QIF 3.0. Established search methods use, for instance, convex hulls, alpha-shapes, or point grids. Fig. 6 shows a grid-based search applied to a planar and cylindrical feature. Using the information carried in the <TopologySet> and <GeometrySet>, a search grid can be generated for each QIF 3.0 face element, using the individual parametric mathematical equations $f_{\text{surf}}, f_{\text{edge}}$ thoroughly documented in the ISO 23952:2020 [30]. The generated point set $\mathcal{A}_i$ is the reference for identifying the neighbored surface point set $\mathcal{B}_i$ of the mesh with the k-nearest neighbor algorithm.

If all three vertices of a triangle $\mathcal{S}_q$ lie within the boundaries of a feature, it is part of the feature and assigned to the subset $\mathcal{T}_i$ – if there are only less than three points of a triangle on the surface, the identified points are either edge points, or a non-surface point has been mistakenly registered:

$$\mathcal{S}_q = \{P_j, P_k, P_l\} \subset \mathcal{T}_i \mid P_j, P_k, P_l \in \mathcal{B}_i; \quad j \neq k \neq l. \tag{1}$$

In this way, a surface mesh can be broken down into its subsets, surface element by surface element, whereby each triangle is associated with exactly one subset $\mathcal{T}_i$. It applies:

$$\mathcal{T}_i \cap \mathcal{T}_j = \emptyset; \quad \forall\, i, j = 1, \ldots, n(\mathcal{T}); \quad i \neq j. \tag{2}$$

As a result, each surface mesh triangle is associated with one <FaceId>. Non-robust algorithms and geometrically complex shapes, however, can lead to triangles not associated at all or multiple times with different features, violating Eq. (2) (see Section 4.1). In addition to a discrete description of the surface, the intrinsic feature characteristics are further known, implicitly creating a hybrid representation model [48] (see Fig. 6, (right)). A semantic link between the discrete geometry representation and the model-based GD&T information is automatically created (see Fig. 6, (right)) since the id-based link between the <Face> elements and the <Feature> and <Characteristic> elements are known (see Fig. 3).

Since the specification information, jointly with the geometrical feature information, only describes the size and shape of the tolerance zones, assumptions on the geometrical shape variations must be made in the prediction stage (see Fig. 4). Various methods have therefore been proposed in the literature for generating shapes with systematic and random deviations in the context of Skin Model Shapes; see, for instance, [41,49]. If the feature's form is considered ideal and only size, location, and orientation deviations are to be represented non-ideal, existing feature-based variation strategies, for instance, as presented in [50], can be adapted since the relevant information is already known from QIF 3.0, making an additional identification of the characteristics from the meshes, such axis, surface normal vector, etc.,

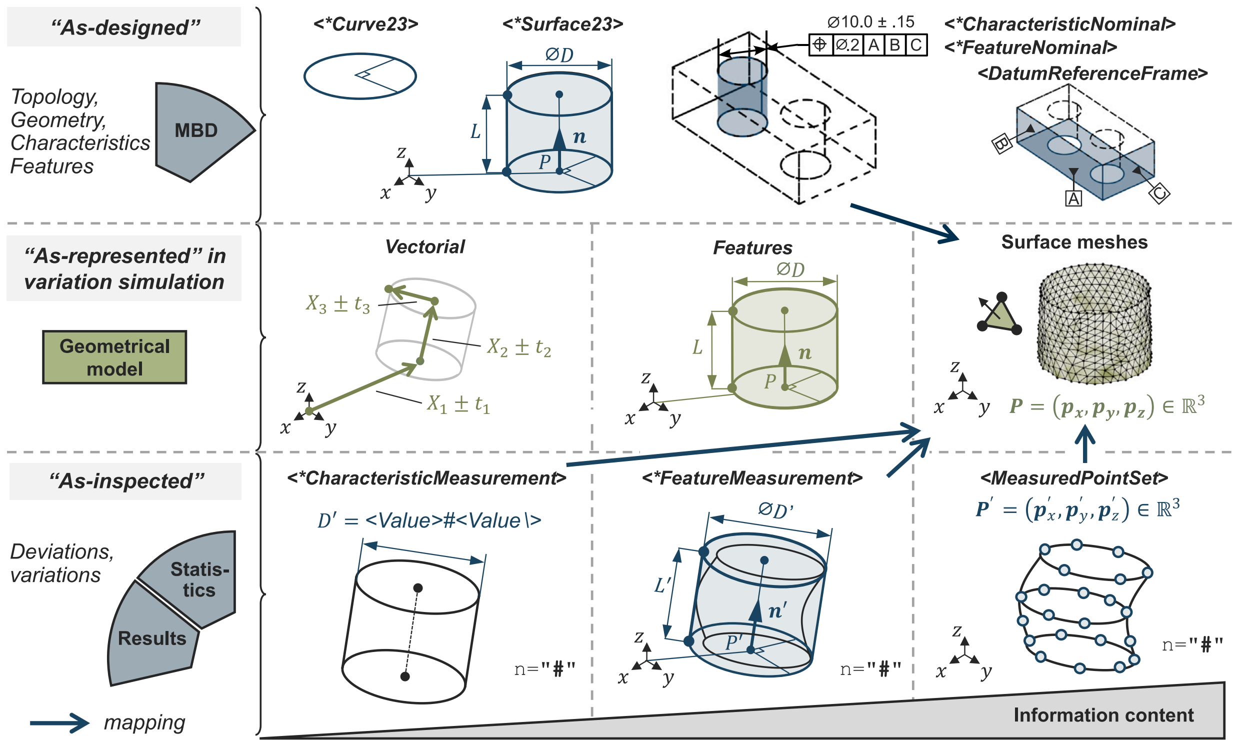

Fig. 5. "As-designed" and "as-inspected" status represented in QIF 3.0 in comparison to the "as-represented" status defined by geometrical models in variation simulation. The figure exemplifies three out of numerous potential geometrical models known from literature.

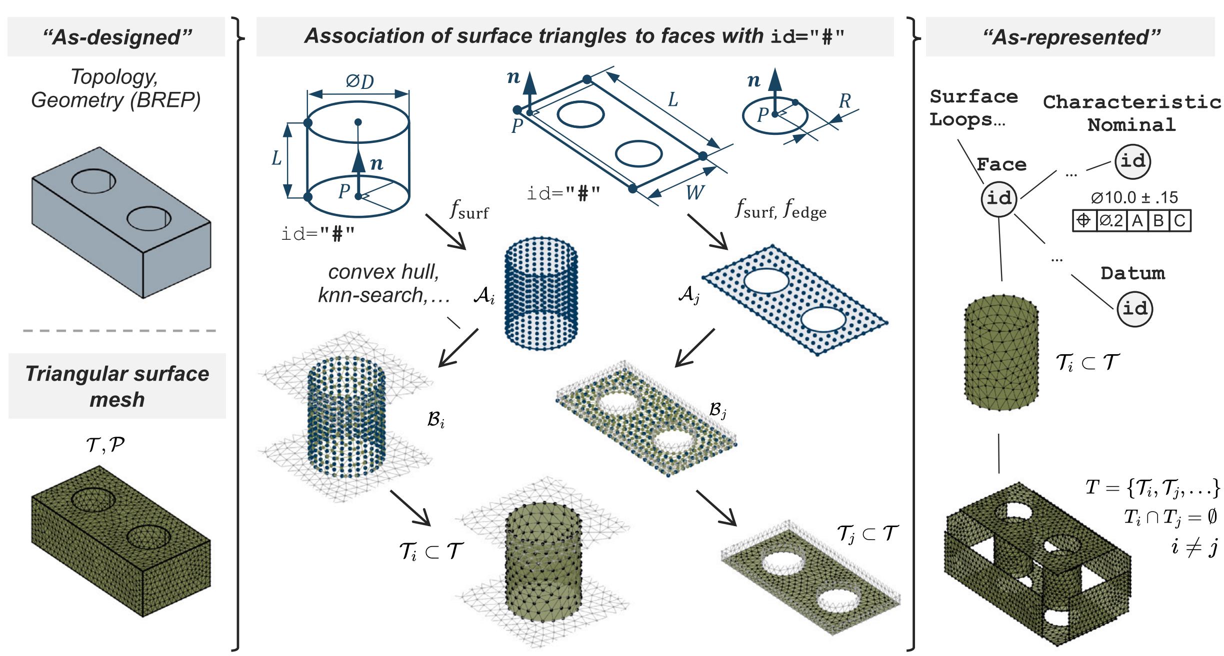

Fig. 6. General principle of automated generation of triangular meshed-based geometrical model for variation simulation using the topology and geometry, features and characteristics information in QIF 3.0.

obsolete. Assumptions on the distributions within the tolerance zones are still needed, as the relevant information is most likely unavailable. Apart from that, QIF 3.0 can carry all the required information to automatically define the *geometrical model* for all the parts involved within an assembly.

The second model needed for variation simulation is the *behavior model*, which sets all the parts in relation to each other and propagates the variations in the assembly. The parts are ideally positioned in the 3D space in QIF 3.0 (see Section 2). However, no information on assembly contacts or joints can be represented in QIF 3.0, and information from CAD environments gets lost during the export. Thus, portions and mating points of the parts must be identified and relatively positioned by bringing them into contact to study the accumulation of the variations on the assembly [51]. Numerous approaches for variation propagation exist in literature suitable for point- and mesh-based shape representations and can be used for variation propagation [51]. These also include mechanisms, such as automatic contact detection algorithms [52], that help find the mating features automatically and reduce the manual effort in defining the *behavior model*, serving as the basis to make statistical predictions in early design stages.

3.2. Enriching the variation simulation model with verification information

If deviation information beyond the specification is available from real (or virtual) measurements, it can be used in the observation stage (see Fig. 4). QIF 3.0 offers three ways to represent measurement information: <*CharacteristicMeasurement>, <*FeatureMeasurement>, and <MeasuredPointSet> (see Fig. 5 (bottom)). Regardless of the chosen strategy (insights on the individual benefits and recommendations are given later in this section), the information is indirectly linked to the respective <FaceId> over the specified <Features> and <Characteristics> and thus directly to the hybrid geometrical model for statistical variation simulation (see Fig. 3).

Statistical predictions One <MeasurementResult> element represents a deviated instance of a characteristic or feature. The relation between the "as-inspected" and "as-designed" status must be identified to use this information within variation simulation. It serves as the bijective function $g : \mathcal{P}_i \rightarrow \mathcal{P}_i'$ of the point set $\mathcal{P}_i$ to itself, helping to map the deviation information onto the mesh-based geometrical model. The bijective function, which at least contains one geometric transformation, depends on the available measurement element, the geometric feature type with its invariances, as well as the specified tolerance type and its related degrees of freedom. For instance, information on the size deviation from the ideal cylinder diameter can be inferred from the <DiameterCharacteristicMeasurement> value, which can be expressed as a scaling operation $\boldsymbol{S}$ in the normal direction $\boldsymbol{v}$ of each point $\mathcal{P}_i$ to the cylinder axis $\boldsymbol{n}$ (see Fig. 7, left). While this information is sufficient for size tolerances, a single measurement value cannot describe a feature's location and orientation. A measured value for a position tolerance, in combination with the specification information on a cylindrical tolerance zone, defines the radial distance between the ideal and deviated cylinder but not the exact location (see Fig. 7 (left)). Missing information must be added, making assumptions, to formulate g as a translation operation $\boldsymbol{T}$ or rotation operation $\boldsymbol{R}$.

<*FeatureMeasurement> elements, in comparison, describe the entire geometry through a set of parameters. Hence, it offers information on deviations in size, location, and orientation, helping to set up g (see Fig. 7 (center)). For both <*CharacteristicMeasurement> and <*FeatureMeasurement> elements, the geometrical model's duality pays off since the features can be used to identify g and the semantic link to the mesh allows the direct application of g to the point subsets $\mathcal{P}_i$.

If discrete individual measuring point information is available for a feature, this information must first be assigned to the respective triangle points $\mathcal{P}_i$. The number of measurement points depends on the selected measurement plan, the device, filtering, and extraction operations [45], so there are usually significant differences between the number of measurement points $\mathcal{P}'_{\text{meas}}$ and mesh points $\mathcal{P}_i$ for a feature i. As a result, the node displacement of each point $\mathcal{P}_l$ is obtained, whereby the shape of the feature can modeled via individual node translations $\boldsymbol{T}_l$ in all three spatial directions (see Fig. 7 (right)).

Since QIF 3.0 models can cover many instances expressed through multiple <MeasurementResults> elements, the individual deviation information can be used to derive the relevant variation information on the magnitude and the distribution of the individual input parameters for the bijective function, including standard geometric transformations as well as additional mesh morphing or decomposition operations to vary the form of the shapes [53]. The information is the basis for generating a representative set of parts with random variations based on the small number of real observations made by inspection to statistically predict the assembly quality for a large batch of products with randomly assembled parts [54]. In case information for individual characteristics is already available as a pre-evaluated <*CharacteristicStats> element (see Fig. 3), it can be used directly. However, it only allows the statistical description of single characteristics of the feature geometry. Alternatively, generative, deep learning approaches offer the possibility for a direct reproducing of a virtual batch of parts with varying characteristics [55] or shapes [49,56].

Digital twin Instead of making statistical predictions mimicking the assembly process by a random pairing of parts, a digital twin strategy for variation simulation based on the general idea of smart assembly can be followed [7] (see Fig. 4). Suppose the real shape is known and an individual digital representative of each part exists. In that case, this potential can be used for increasing the assembly quality through an individual, pair-wise matching of parts (= selective assembly) and making individual adjustments in the assembly process, such as the joining sequence or fixture locators [7,57]. In QIF 3.0, the link between the real parts and virtual parts, and thus a central part of the digital thread, is preserved by referencing the respective measurement result element to the real part instance through an <ActualComponent> element (see Section 2.2). In comparison to statistical predictions, the measurement results for each feature are directly used to represent the inspected and deviated status of each actual part. Finding relevant information in the measurement results for variation modeling is not applicable. The deviations are directly mapped to the geometrical model using geometric transformation operations, as illustrated in Fig. 7, and further used for a subsequent smart virtual assembly.

The single values carried in the <*CharacteristicMeasurement> elements are sufficient for statistical quality control applications in series production. They can also provide valuable input on the achievable accuracies for variation simulation. However, reducing the measured information content to one value requires additional assumptions on location, orientation, and form of the quality critical features and limits QIF 3.0's benefits for integrating inspection information into variation simulation. Mapping the information obtained through measurements via <*FeatureMeasurement> elements is more beneficial for a realistic simulation of the behavior of assemblies in 3D, both to make statistical predictions and digital twin applications, is recommended. Adding the discrete measurement points as <MeasuredPointSet> elements is mainly beneficial when form deviations of the shapes are critical and shall be represented in simulation, particularly when point- and mesh-based representation models are used.

Suppose part inspection is further used to capture different statuses of the part geometries and link them via QIF 3.0, like at various stages of manufacturing or after use. In that case, they can also be used for adaptive manufacturing in series production [58] and re-manufacturing, and repair strategies for products in use [59].

4. Discussion on the challenges and future prospects

The previous sections showed the potential of QIF 3.0 for model-based variation simulation and its application at various points in the geometry assurance process, exploiting the conceptual benefits of QIF 3.0. A comprehensive evaluation of its applicability and challenges for a profitable application at industrial scales and complexity requires realizing the entire digital thread for geometry assurance. Communication between the involved CAD, CAT, CAI (Computer Aided Inspection), and actual inspection systems is crucial so that the information can be semantically represented in the variation simulation model for different geometry assurance activities. The related challenges are discussed in the following before the whole chain can be established in future works.

4.1. Challenges

Generating QIF 3.0 from CAD When generating neutral exchange files as software-independent data carriers within CAD environments, the model-based GD&T information must remain human-readable, computer-interpretable, and be free of loss. Compared to STEP AP242,

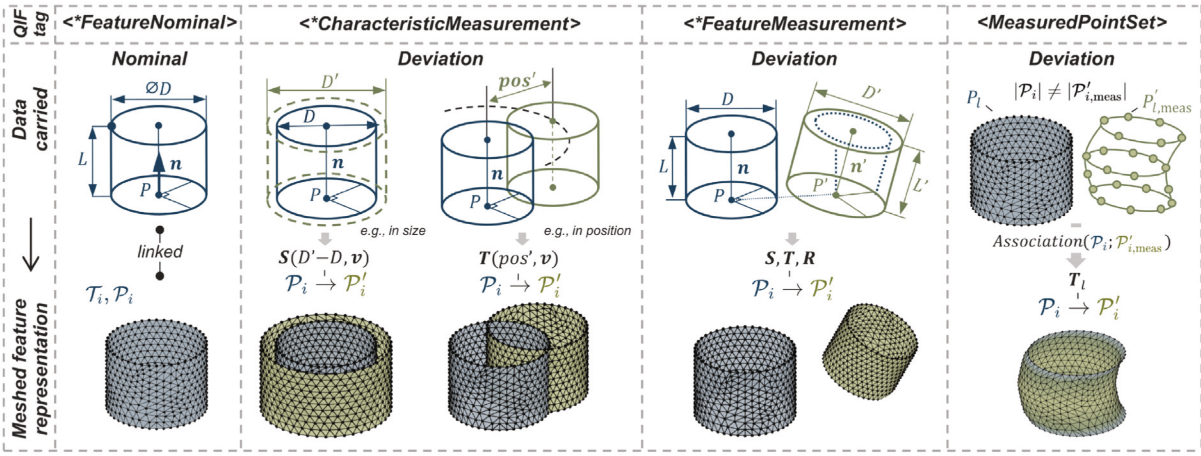

Fig. 7. Using verification information from QIF 3.0 for deviation/variation modeling of meshed features in variation simulation.

CAD import and export of QIF 3.0 are still limited at the current state of the art. First CAD software vendors, however, have started to implement QIF functionalities in their software, for instance, Autodesk® in the recent releases of Autodesk® Inventor Professional® [60]. It is supposed others will follow soon. Besides, third-party translators, for instance, Capvidia MBDVidia [61] or Elysium [62], support the translation of common native CAD formats.

Using QIF 3.0 for CAI Since the development of QIF is primarily motivated by the inspection perspective, it has become much more established for CAI and is already implemented in several proprietary software solutions for inspection planning, execution, and data processing using tactile and optical measurement devices. Examples include Renishaw MODUS™ [63], Hexagon PC-DMIS® [64], ZEISS CALYPSO® [65], Mitutoyo® MCOSMOS® in combination with MiCAT Planner™ [66,67], and PolyWorks Inspector™ [68] – to emphasize the range and variety at this point and not to assess or advertise specific software solutions. Apart from the standard's conceptual possibility and the existing practical solutions for model-based CAI, strategies for storing the measurement results within QIF must be developed, including the software's capabilities to append measurement results to existing QIF 3.0 files. This also includes decisions on whether the raw data set and all measurement points must be retained. i.e., the "as-inspected" status must be known and preserved in detail over the total product life cycle stage, or if condensed information, in terms of reduced measurement points set, through measured characteristics or feature information, is sufficient to cope with the Big Data issues [5,57,69].

Bringing QIF 3.0 into CAT Interfaces are essential to automatically bring the information from design and inspection without any information loss into variation simulation. Most CAT systems, however, do not support importing QIF 3.0 files so far. Section 3.1 proposed an automatic mapping strategy using QIF 3.0. Real-world examples are, however, more complicated and challenging than the presented example. They cover the whole range of GD&T according to the referred ASME or ISO standard in the `<StandardsDefinitions>` elements, i.e., different size, location, orientation, and form tolerance callouts, additional datum reference entries, and further information, e.g., on tolerance zone types and modifiers (see Fig. 8 (top)). Furthermore, the geometry elements vary in type, orientation, size, and boundaries within one part. Besides standard geometries of planar, cylindrical, or conical shape, spherical, toroidal, or non-uniform rational basis spline (NURBS) elements are needed to represent curved free-form surfaces (see Fig. 8 (center)). Furthermore, smooth transitions between features are much more error-prone for mesh segmentation than sharp edges (see Fig. 8 (bottom)).

To finally evaluate the suitability of QIF-based variation simulation for industrial problems, an automatic mapping strategy following the general principle given in Section 3.1 and Fig. 6 was elaborated and prototypically implemented in MATLAB® R2023b. A disc brake assembly modeled in Autodesk® Inventor Professional® 2025, consisting of multiple parts with semantic tolerance specifications, served as a case study (see Fig. 9(a)). The derived QIF models are used for an automatic model setup for variation simulation, partitioning the triangular surface meshes generated in Ansys® 2024 R1 into features and associating the respective topology, geometry, and tolerance information to the mesh segments. A grid-based search method is used to first discretize the shape of the feature into a number of search points to identify the vertices of surface triangles for the respective feature type based on the k-nearest neighbor algorithm (in line with Fig. 6). Non-convex planar features with multi-polynomial outer and multiple inner boundaries are handled as two-dimensional point-in-polygon-problems [70] and solved with in-built algorithms.

Additional verification routines are necessary to solve contradictions caused by multiple assignments of triangles that violate the condition in Eq. (2). One suitable way is to use the parametric surface description within QIF 3.0, which is given as a mathematical function of parameters. These functions describe QIF 3.0 features unambiguously in the Euclidean space $\mathbb{R}^3$ with a non-linear system of three equations for the x, y, and z direction [30]. They are already used to generate the search grid (see Section 3.1) and can further be used for the final verification. Hence, a point P_i lies only on a surface if there is a valid solution for this non-linear equation system within the parameter space and their boundaries. Only if there is a valid solution for all three vertices of a triangle, the triangle belongs to the associated feature and not to any other feature. Numerical optimization is helpful in solving the highly non-linear equation systems for each multiple-times associated triangle. Following this strategy, an unambiguous association of each surface triangle to a QIF 3.0 feature was achieved for all parts of the disc brake assembly. Fig. 9(b) provides an overview of the meshed parts broken down into their color-coded features.

For the more simple models, the piston and caliper pad, which only have sharp edges, all triangles were unambiguously associated with one feature in low computing times of less than 2s on a personal workstation (32 GB RAM, Core i7-1370P). Models with a higher number of features – the spindle, for instance, covers a total of 360 features – and smooth edges led to computing times between 16s and 456s. The optimization-based routine to solve the multiple triangle association problem dominates the computing time. However, segmenting the entire mesh for variation simulation is usually unnecessary. Instead, only features involved in the tolerance chain must be identified, reducing the computational effort to a few relevant features. The average effort decreases to 2 s per part for the given case study (see Tables B.1–B.6).

The specification information annotated in CAD was transferred without any loss to the meshes, which is essential to automatically set

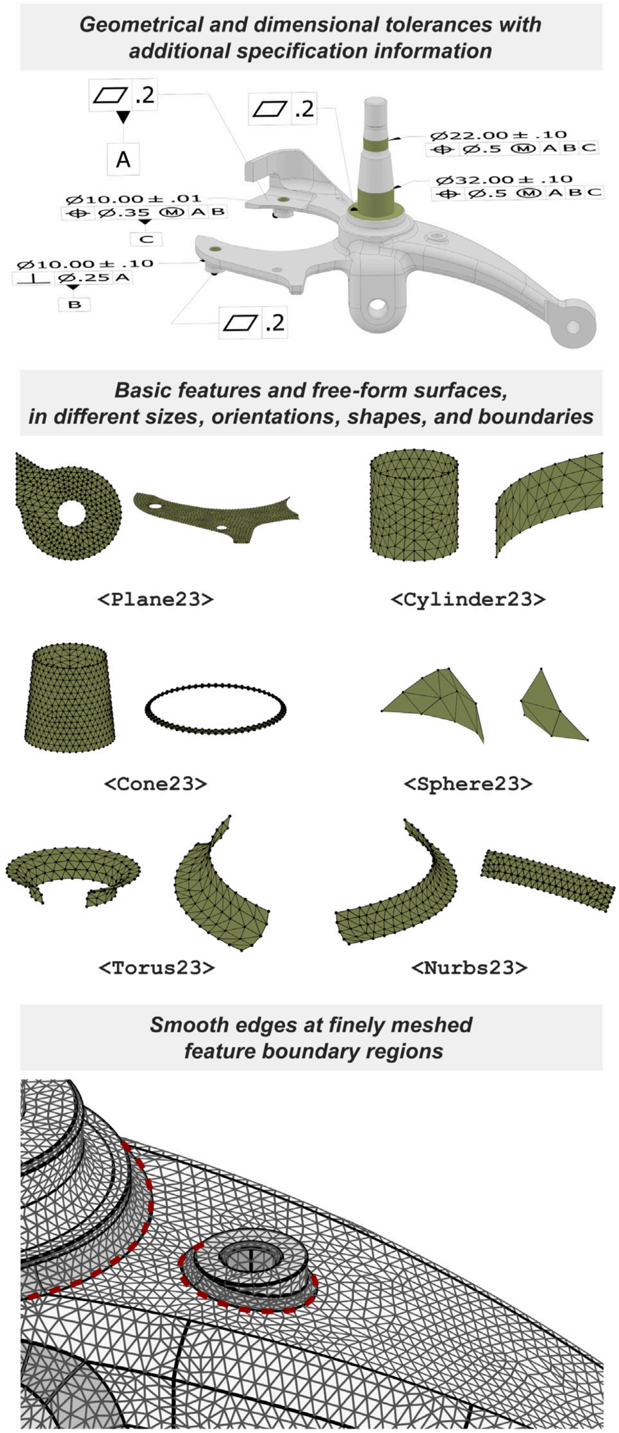

Fig. 8. Challenges in morphing QIF 3.0 information to meshes for variation simulation, exemplary highlighted for the spindle of the disc brake assembly case study given in details in Appendix B.

up the hybrid geometrical model required for all variation simulation applications. However, keeping the link between the "as-represented" and the GD&T information is further important since the QIF 3.0 `<Characteristics>` and `<Features>` elements link part geometries with measurement information obtained in the observation stages. Hence, the present approach provides an efficient solution to automatically define geometrical models for industrial complex problems in reasonable computing times. Since it is suitable for point- and mesh-based representation models, the MBD-based approach can be integrated into the skin model shape concept as well as finite element-based variation simulation frameworks based on surface meshes. Further details on the case study and the results can be found in Appendix B.

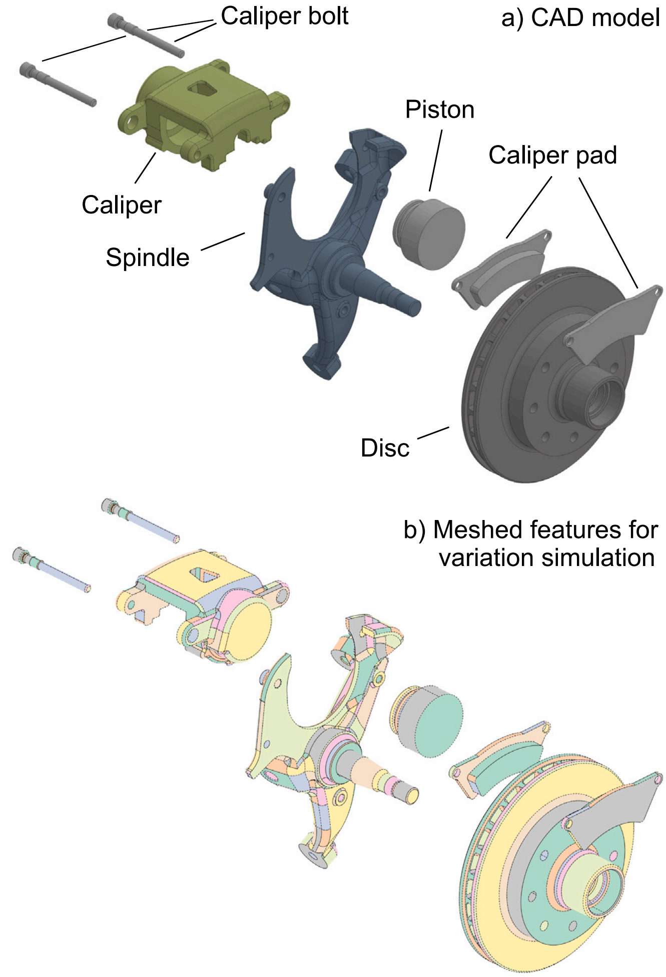

Fig. 9. Case study: (a) overview of the disc brake assembly in CAD; (b) hybrid geometrical model with meshed features for variation simulation. Meshes are hidden for better visibility but are given in Appendix B.

Going beyond pure import, it is worth studying whether and to what extent QIF 3.0 can store CAT model and result information. Since it is designed to capture different representations within one hybrid model [30], the "as-represented" status expressed through mesh, point, and parametric features may be captured jointly with the "as-designed" and "as-inspected" status within one QIF 3.0 model. QIF 3.0 is well elaborated on the part level to set up the *geometrical model*. However, carrying information on the assembly level for the *behavior model*, such as requirements, like flush and gaps between parts, or the physical behavior of assemblies under variations, is not possible with the sole use of QIF. Consequently, QIF 3.0 does not bring benefits in automation and information enrichment for propagating variations on the assembly level, but the mechanisms developed in the literature for accumulating the part variations can still be used. To overcome the gaps in the digital thread newly opened by QIF 3.0, additional sources of information are useful to complement the part-centric quality information carried within QIF 3.0. Research in the MBD context shows that semantically linking multiple standardized information carriers is beneficial to exploit the potentials but also to overcome the limitations of single neutral exchange files [25,29]. Defining a mutual knowledge base supporting the entire geometry assurance process, not solely but substantially based on QIF 3.0, can be a promising solution for industrial applications and should be the focus of further research studies.

In summary, it can be stated that the basic instruments and infrastructure for implementing the whole digital thread for geometry assurance, as presented in Section 3, are given. However, there is still space for improvement and expansion, enhancing a final practical implementation and offering prospects beyond the benefits discussed.

4.2. Future prospects

The main strength of QIF 3.0 compared to STEP AP242 lies in the MBD representation of measurement information. The real part geometries inspected via the various life cycle stages can be persistently linked to the nominal geometry via identification designators and simultaneously allow an external reference to the actual components. Storing additional information, such as measurement device, time, strategy, etc., in QIF 3.0 helps to ensure traceability. Hence, each measurement can be characterized by the sensor, etc., used, referencing elements given in the QIF 3.0 resources information model [30] (see Fig. 1). Besides traceability, this offers further potentials; for instance, with repeated inspection of the same part features, it is possible to evaluate measurement repeatability and consider local measurement uncertainties in variation simulation and digital twin [71,72].

The "as-inspected" statuses of a life cycle can further be used for the subsequent cycles of similar products or different products but composed of parts with similar part feature geometries. In this way, access to measurement data can help to reduce the assumptions in the prediction phase and enrich the simulation with knowledge from previous products in concept and pre-product, either directly or through additional fused knowledge bases. Referencing the real parts in QIF 3.0 supports the vision of a thorough digital product passport supporting a circular economy [73].

5. Conclusion and outlook

The central motivation of QIF 3.0 is to improve manufacturing quality workflows by exploiting the benefits of MBD for quality inspection-related activities. This article examined the general advantages of QIF 3.0 and contrasted it with the needs in geometry assurance and variations simulation. The results indicate that gaps in the digital thread's information flow can be closed. The semantic model-based aggregation of specification and verification information in QIF 3.0 is beneficial for automating variation simulation modeling steps and bringing inspection data into the digital geometry assurance process. This, however, implies that CAT tools comprise mechanisms to read and interpret the relevant information on the "as-designed" and "as-inspected" status and map them to the chosen representation model type, serving as an essential basis for making general decisions on a statistical basis or individual ones using digital twins. The proposed solution for mapping QIF 3.0 product specification and verification information to mesh-based geometry representations proves its applicability to industrially complex use cases and exemplifies the strengths of QIF 3.0 for variation simulation.

Despite the elaborated benefits on part level, gaps in the digital thread are not closed yet. There is a lack of information on the assembly level mitigating the automation of variation simulation. Future research on combining QIF 3.0 with other information carriers in a mutual knowledge base, for instance, based on the Web Ontology Language (OWL), is thus necessary to enhance the information flow within the geometry assurance process. A practical implementation of the digital thread for geometry assurance and its benchmark with case studies is essential to complement the methodical studies to identify further needs and opportunities.

CRediT authorship contribution statement

Martin Roth: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abolfazl Rezaei Aderiani:** Writing – review & editing, Methodology. **Edward Morse:** Writing – review & editing, Writing – original draft, Methodology. **Kristina Wärmefjord:** Writing – review & editing, Supervision, Project administration, Methodology. **Rikard Söderberg:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

Dr. Morse is a member of the DMSC and is involved in the development of QIF 3.0. This participation provides Dr. Morse with insight into the structure and development of QIF, but there is no financial or other benefit to his contribution. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Representation of assemblies in QIF 3.0

See Fig. A.1.

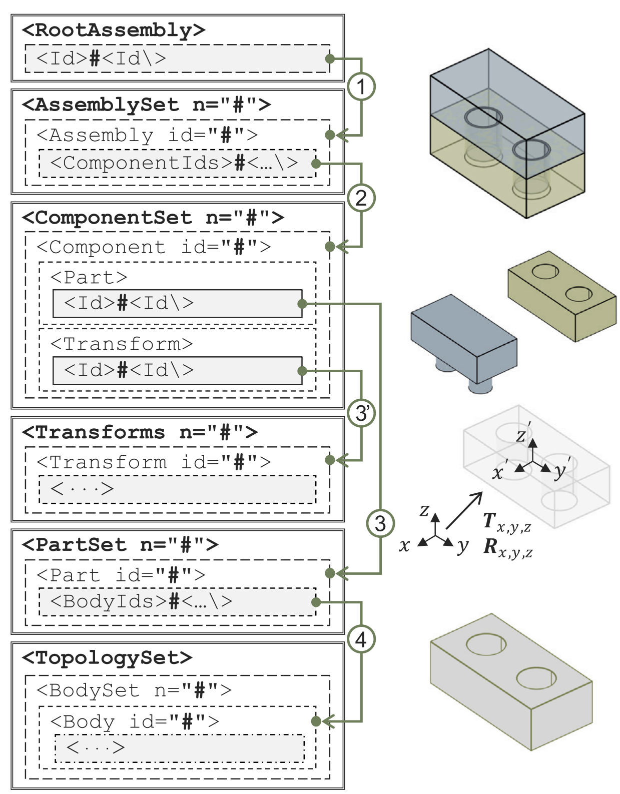


Fig. A.1. Representing assemblies within the <Product> element of a <QIFDocument>.

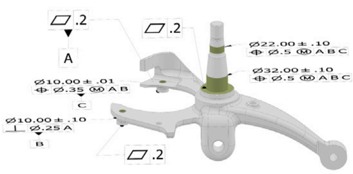
Appendix B. Details on the disc brake example

See Tables B.1–B.6.

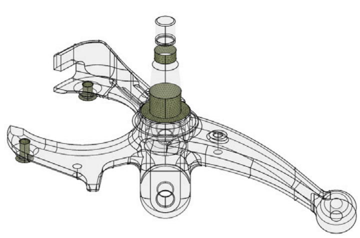
Table B.1
Disc brake assembly – Spindle: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

Part: spindle

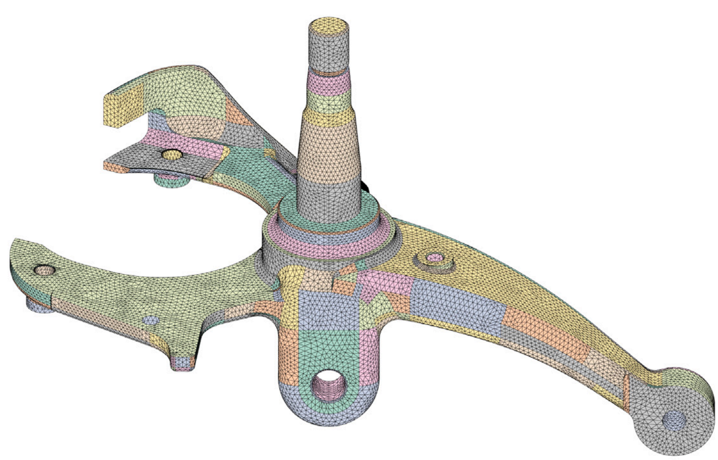
CAD model with PMI



Surface mesh: tolerance and datum features



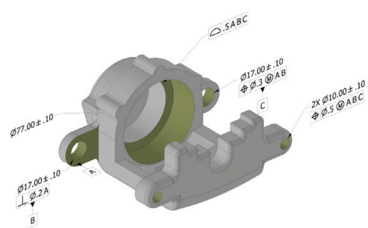
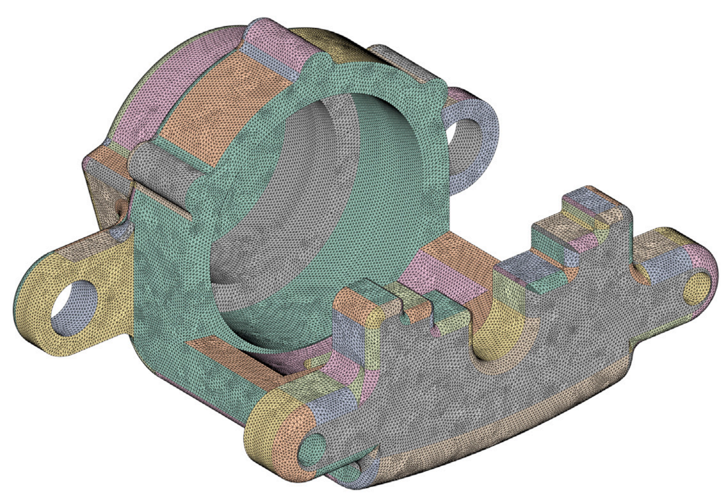
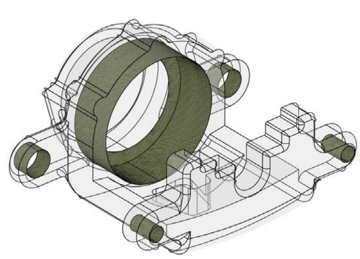
Surface mesh: split into features



Associated surfaces		Associated characteristics		Datums	Surface mesh	
Name	Count	Name	Count	Count	$\|\mathcal{T}\|$	$\|\mathcal{P}\|$
Plane23	61	FlatnessCharacteristic	3	3	47,168	23,574
Cylinder23	111	PerpendicularityCharacteristic	1			
Cone23	15	PositionCharacteristic	3			
Sphere23	4	DiameterCharacteristic	4			
Torus23	34		11			
Nurbs23	135					
	360					

Computing times	
QIF 3.0 parsing	3.61 s
Segmentation: total surface mesh	200.20 s
Segmentation: GD&T features only	1.16 s

Table B.2
Disc brake assembly – Caliper: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

Part: caliper	
CAD model with PMI	**Surface mesh: split into features**
	
Surface mesh: tolerance and datum features	
	

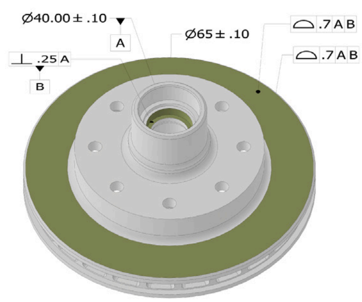
Associated surfaces		Associated characteristics		Datums	Surface mesh	
Name	**Count**	**Name**	**Count**	**Count**	$\lvert\mathcal{T}\rvert$	$\lvert\mathcal{P}\rvert$
Plane23	43	PerpendicularityCharacteristic	1	3	46,286	23,135
Cylinder23	78	PositionCharacteristic	2			
Sphere23	1	SurfaceProfileCharacteristic	1			
Torus23	34	DiameterCharacteristic	4			
Nurbs23	50		8			
	206					

Computing times	
QIF 3.0 parsing	1.80 s
Segmentation: total surface mesh	455.18 s
Segmentation: GD&T features only	1.24 s

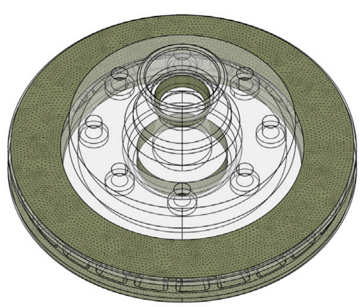
Table B.3
Disc brake assembly – Disc: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

Part: disc

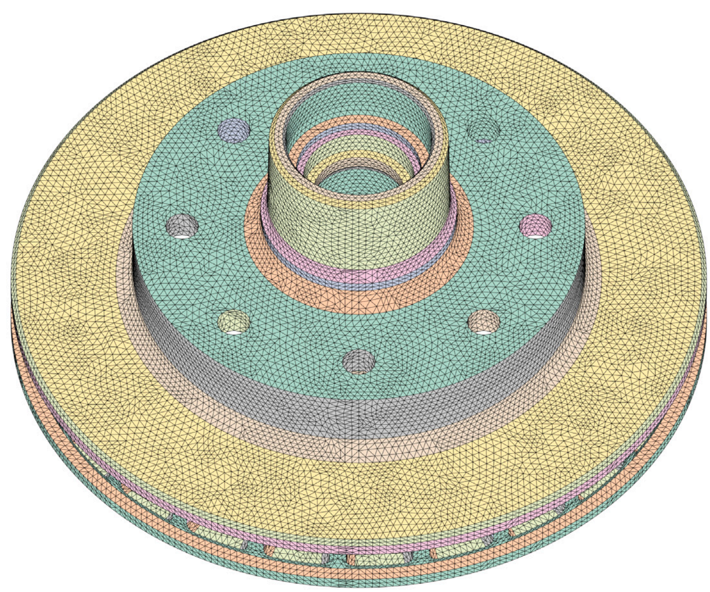
CAD model with PMI



Surface mesh: tolerance and datum features



Surface mesh: split into features



Associated surfaces	
Name	**Count**
Plane23	123
Cylinder23	130
Cone23	9
Sphere23	4
	266

Associated characteristics	
Name	**Count**
PerpendicularityCharacteristic	1
SurfaceProfileCharacteristic	2
DiameterCharacteristic	2
	5

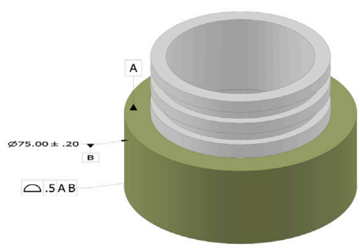
Datums	Surface mesh	
Count	$\lvert\mathcal{T}\rvert$	$\lvert\mathcal{P}\rvert$
2	90,704	45,286

Computing times	
QIF 3.0 parsing	2.24 s
Segmentation: total surface mesh	24.60 s
Segmentation: GD&T features only	0.40 s

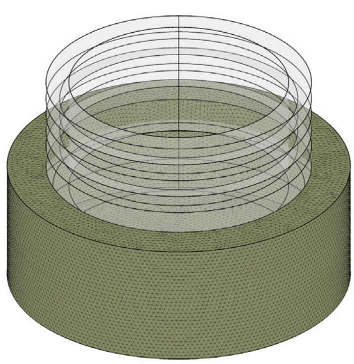
Table B.4
Disc brake assembly – Piston: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

Part: piston

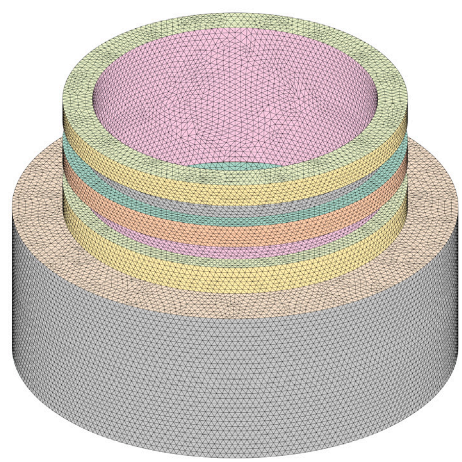
CAD model with PMI



Surface mesh: tolerance and datum features



Surface mesh: split into features



Associated surfaces	
Name	**Count**
Plane23	9
Cylinder23	8
Torus23	2
	19

Associated characteristics	
Name	**Count**
SurfaceProfileCharacteristic	1
DiameterCharacteristic	1
	2

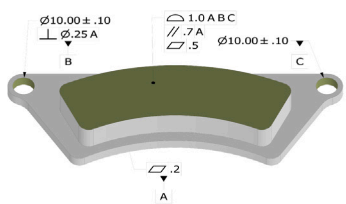
Datums	Surface mesh	
Count	$\lvert\mathcal{T}\rvert$	$\lvert\mathcal{P}\rvert$
2	71,056	35,530

Computing times	
QIF 3.0 parsing	0.63 s
Segmentation: total surface mesh	1.13 s
Segmentation: GD&T features only	0.24 s

Table B.5
Disc brake assembly – Caliper pad: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

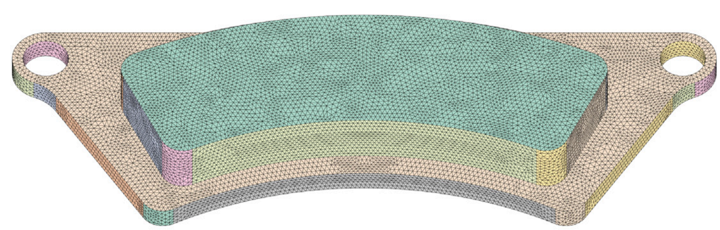
Part: caliper pad

CAD model with PMI



Surface mesh: tolerance and datum features

Surface mesh: split into features



Associated surfaces: Name	Count
Plane23	9
Cylinder23	16
	25

Associated characteristics: Name	Count
FlatnessCharacteristic	2
ParallelismCharacteristicDefinition	1
PerpendicularityCharacteristicDefinition	1
PositionCharacteristicDefinition	1
SurfaceProfileCharacteristicDefinition	1
DiameterCharacteristicDefinition	1
	7

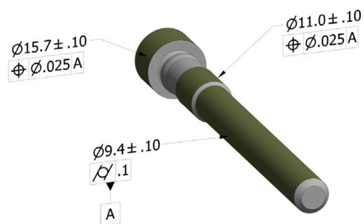
Datums: Count	Surface mesh: $\|\mathcal{T}\|$	$\|\mathcal{P}\|$
3	37,000	18,498

Computing times	
QIF 3.0 parsing	0.70 s
Segmentation: total surface mesh	1.23 s
Segmentation: GD&T features only	0.68 s

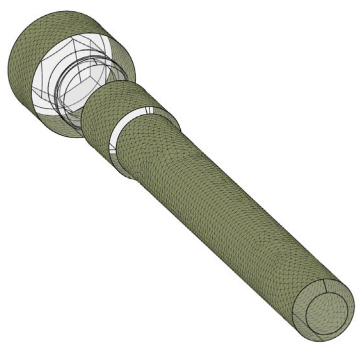
Table B.6
Disc brake assembly – Caliper bolt: specified tolerances as semantic GD&Ts in CAD, segmented meshes, associated QIF 3.0 features and characteristics, and further details.

Part: caliper bolt

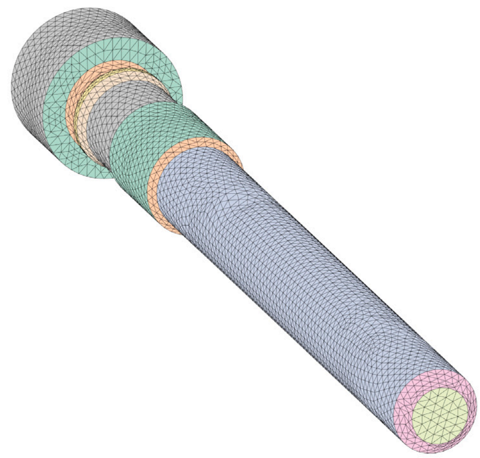
CAD model with PMI



Surface mesh: tolerance and datum features



Surface mesh: split into features



Associated surfaces: Name	Count
Plane23	10
Cylinder23	6
Cone23	6
Torus23	2
	24

Associated characteristics: Name	Count
CylindricityCharacteristic	1
PositionCharacteristic	2
DiameterCharacteristic	3
	6

Datums: Count	Surface mesh: $\|\mathcal{T}\|$	Surface mesh: $\|\mathcal{P}\|$
1	7,826	3,915

Computing times	
QIF 3.0 parsing	0.68 s
Segmentation: total surface mesh	15.56 s
Segmentation: GD&T features only	0.35 s

Data availability

Data will be made available on request.

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