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Model-based definition in computer aided tolerance analyses

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Abstract

Recent advancements in means of data collection and utilization have stepped forward to the realization of model-based definition approaches in product and production development processes. This realization is further facilitated by the presentation of open-source standards for model-based definition including STEP AP 242 and QIF 3.0. As a result, engineers are empowered with a significant amount of data to improve the development processes, particularly the tolerancing and metrology processes. This paper briefly reviews the tolerancing methods and MBD open standards. Subsequently, integration of MBD, particularly QIF 3.0 and STEP AP 242, into CAT methods including the opportunities and challenges in this regard are discussed. The main breakthrough in these standards is the semantic representation of tolerancing data in the models. However, the existing methods of modeling and analyzing tolerance information are diverse and not all these methods can utilize the new standards in the same manner. The potential usages of the new standards in different tolerance modeling techniques are reviewed. Furthermore, the research gaps and wishes for further improvements in the tolerance analysis era through model-based definition are discussed.

Keywords: Model-based definition; Computer aided tolerancing; QIF standard; STEP 242 standard;

1. Introduction

Model-based definition (MBD) is defined as an approach of product and production development in which different stages of a product life-cycle interact by utilizing a common 3D model i.e. there is one source of the truth for all activities. Traditionally, 2D drawings have been used for communication among different design and production activities. Nevertheless, in the MBD approach, the goal is to substitute these drawings with a 3D model [21].

The utilization of MBD seems to be a game-changer in the near future of production. Based on a study by Herron et al. [10] realization of MBD in the industry can save 10 Billion USD by substituting 2D drawings in the US. In another study, [9], STEP AP 242 and QIF models, and MtConnect platform are utilized for generating a digital thread between the model, machining, and measurement tools. As a result, 15% more efficiency in machining, 35% less programming, and 50% easier operation has been achieved.

The main characteristic of MBD models is the semantic representation of product manufacturing information (PMI), particularly geometric and dimensional tolerances (GD&T). The semantic representation commonly means the GD&T data are not attached to the model as pure texts and symbols but as characteristics of geometric features that can be utilized by computers programs.

The shift through MBD is accelerating by the emergence of new paradigms and concepts, particularly Industry 4.0, digital thread, Internet of Things, and data-driven development and design [24]. Based on the current trend in research and industry, MBD has a high chance of substituting the 2D drawings which are still the dominant type of communication of PMIs. The main question in this regard is: How can MBD influence the era of computer-aided tolerancing (CAT) particularly tolerance analyses? This paper aims to raise this question and discuss its answer by assessing the potential opportunities and challenges of MBD for CAT analyses. To achieve this goal, different CAT analysis methods are reviewed in Section 2. Thereafter, Section 3 reviews three main MBD open-standards. Subsequently, the integration of MBD in CAT is discussed in Section 4.

2. Tolerance analysis methods

Tolerancing and CAT methods and tools have been reviewed and classified from different points of view comprehensively [2, 20, 14, 22]. Hence, for a detailed review, the reader is referred to these studies. However, for this paper, a review of criteria with which these methods can be categorized and how every method fits in each category is presented. To achieve this goal, the utilized terminology in these studies is clarified firstly.

Tolerance information models (data models) is a term utilized by Qin et al. [20] for a model that can be used to represent or interpret GD&Ts. They have divided these models into two categories of *representation models* and *interpretation models*. Based on this classification, an interpretation model is a mathematical model i.e. formulation of tolerances. Examples of this category are the offsetting model, parameter model, vector equation model, variational surface model, kinematic model, generalized interval model, degree of freedom model, and tolerance-map (T-Map) model. On the other hand, a representation model is defined as a model to represent the semantics that is defined by an interpretation model, i.e. a computer programmable model of a representation model. EXPRESS model, technologically and topologically related surfaces (TTRS), unified modeling language (UML) models, extensive markup language (XML) model, category theory model, GeoSpelling model, relationship model and ontology web language (OWL) model are examples that are categorized as representation models by these authors. Among these information models, OWL, XML and EXPRESS are directly computer-readable. The other representation models should be translated using a computer programming language.

Tolerance analysis model is utilized as a more general term than tolerance information model, commonly referring to any mathematical or physical modeling [2] to interpret or represent the GD&Ts, simulating the variation propagation and evaluating the geometrical or functional requirements. Accordingly, the entire procedure of tolerance analysis can be divided into four applications of interpreting the GD&Ts, representing the GD&Ts, simulating the variation propagation, and evaluating the requirements. A tolerance analysis model may cover a portion or entire of this procedure. Figure 1 presents a schematic of this procedure and the application of each model in this process.

Tolerance analysis models are not limited to the list presented in Figure 1, but these methods are relatively more established [2, 20, 22]. A prerequisite for every simulation model is having a data model. Most of the simulation models presented, require their representation and interpretation models.

The TTRS model [5], Matrix model [6], and Jacobian-torsor model [13], are developed based on the screw-theory. Accordingly, a kinematic relationship between the features and datum is generated where the parts are links that connect these objects. Consequently, these methods are proper for rigid parts.

Two methods of T-Map® (Patent No. US6963824) and deviation domain [8] are based on defining the deviation spaces. A hypothetical space that represents all possible versions of a deviated feature is determined in these methods.

Vector loop model [3] determines the variation propagation for a feature by generating a loop of vectors for that feature. The distance between every two joints and their kinematic parameters are each represented by a vector. Thereafter, for each loop, a non-linear equation can be derived from which the deviations will be determined. A problem with this method is that the variation propagation is calculated only in the loop direction at a time and the interaction of different loop directions is not considered.

GapSpace [28] is another model, both for interpreting the tolerances and analyzing their propagation. The data model in this method consists of two sets of information. One set includes all information regarding the joints or gaps (*liaison*), and the other set contains geometric relations among them (*directed dimension tree*). Thereafter, the probability density function (pdf) of deviations are integrated into the model, and pdfs of the propagated variations are determined.

All aforementioned methods are mainly concerned with tolerance analysis of products with movable joints and gaps. Pumps, engines, and turbomachines are examples of these types of products. However, another common type of product in the industry is welded assemblies, particularly sheet metals. A body in white (BIW), an airplane structure, or other structures are commonly an assembly of permanent joints, mainly welds, and rivets. The key factor in the variation propagation of these assemblies is the spring-back that occurs after releasing the welded structure from the fixtures. This factor, in addition to the contact areas between the parts, adds to the complexities of such problems. The principle approach of tolerance analysis for these problems is to simulate the assembly process by utilizing finite element methods (FEM). An assembly procedure of such requires at least two FE simulations. One for capturing the part deformations when they are located in the fixtures, and one for determining the deformations when the assembly is released from the fixture. To conduct a statistical analysis using this method, Monte Carlo simulations should be conducted. Consequently, a massive number of simulations are required which can be computationally expensive. Method of influence coefficients (MIC) [16] addresses this problem by developing a linear relationship between the deviation of a point before and after the assembly procedure using only two FE simulations. However, the physics of these problems is not linear by nature because the contact points between the welded parts can change depending on the deviation of the incoming parts for the assembly. Dahlström et al. [4], and Lindau et al. [15] have addressed this problem for welded assemblies and Lupuleac et al. [17] for riveted assemblies.

The representation model of FE-based methods is mainly an FE mesh. This mesh can represent deviations either by adding deviated nodes or morphing to the nominal mesh. Skin modeling is a method of determining the deviations in the mesh by considering a random microscopic deviation and a systematic macroscopic deviation waive [2].

Numerous criteria are utilized to classify the tolerance analysis methods. Analysis type or analysis technique method is one of the foremost criteria. There are typically two analysis types: the worst case and the statistical. Statistical analysis can be conducted either by the Monte Carlo method, or residual sum of squares (RSS). Statistical methods are commonly preferred because they represent closer results to reality than worst-case methods. Therefore, the methods that can only handle worst-case analysis are not presented in this paper.

Another criterion is being feature-based or point-based. In point-based methods, the variations are defined and calculated

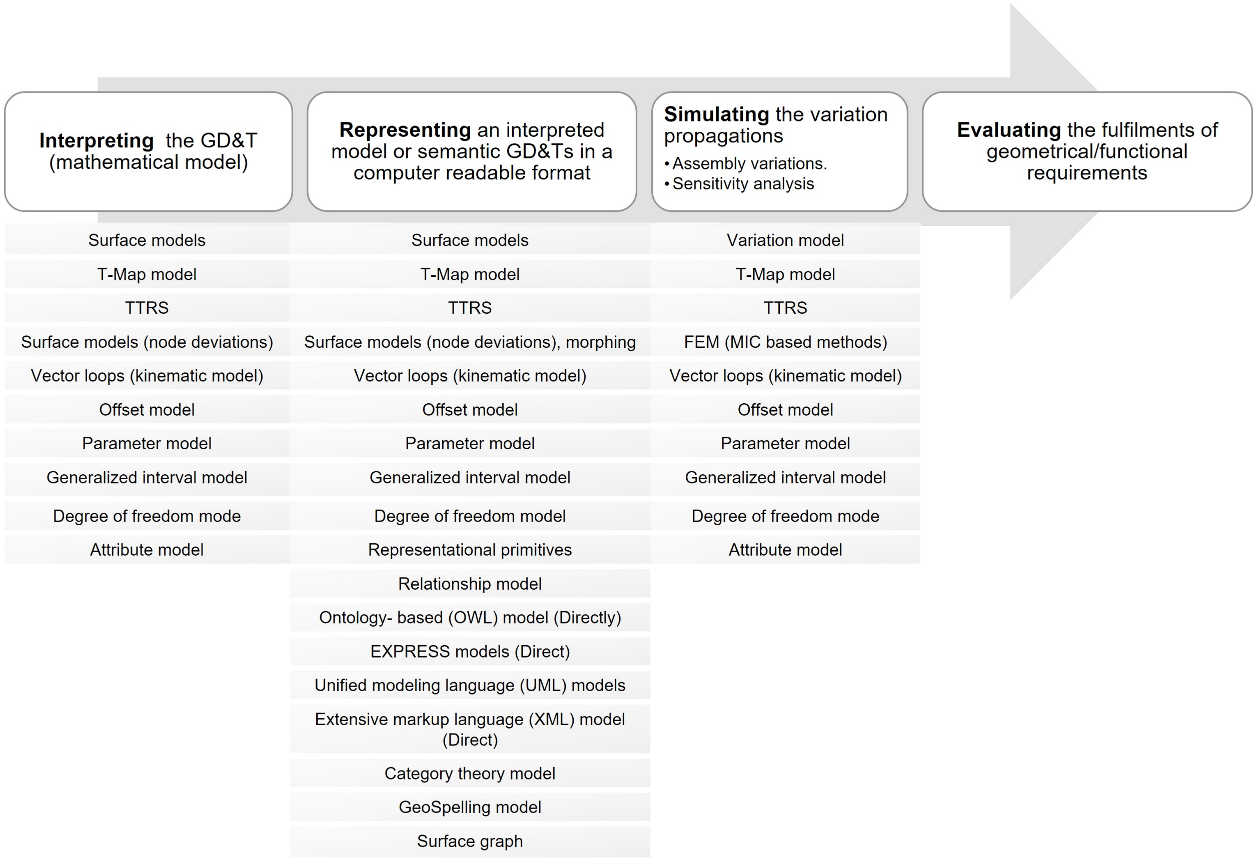

Fig. 1. A general CAT process and how different models can be utilized in it.

for points. On the other hand, in feature-based methods, the variations are defined and analyzed directly as characteristics of features. Slots, circles, and cylinders are examples of these features. To utilize a point-based method for defined variations on features, a translation from feature deviations to point deviations is required.

The joint types of assembly in the product are another important criterion. The joint types can be divided into two categories: movable (kinematic) joints and fixed joints e.g. welds and rivets. Commonly a tolerance analysis method is proper for only one of these joint types. The fixed joint assemblies can be further categorized as compliant and rigid assemblies. Moreover, some of these methods are compatible with considering the contact areas. Figure 2 visualizes these criteria and how each tolerance analysis method fits into each category.

There are dozens of other criteria that are not presented in Figure 2 due to their relatively lower importance in the context of MBD. To categorize the methods based on their scale of utilization in the industry, the usage of a method for solving industrial-scale problems in publications [22] in addition to its utilization in the main commercial CAT programs are evaluated. Among the commercial CAT programs, 3DCS, RD&T, VSA, and eM-TolMate use FE-based methods for compliant assemblies and matrix-based methods for rigid assemblies. Several programs including SolidWorks TolAnalyst, CETOL 6σ, and SigmundWork use vector loop-based algorithms. Moreover, MECAmaster utilizes the torsor method. Also, CATIA FTD is a tolerancing advisor that utilizes the TTRS method.

3. MBD open-standards

Neutral data models play a crucial role in reducing the number of model format translations for using a model in different programs. Neutral formats facilitate the collaboration of different parties without requiring them to have the same program and data format. A neutral format is commonly defined and maintained through an open standard. IGES was the first successful neutral format that was utilized in industrial scales. However, by introducing STEP format in ISO 103030 Standard, STEP took the place of IGES and it is still the most used neutral CAD format [20]. The main trend in the last decades in the most common neutral open standards has been shifting toward facilitating MBD. This section briefly reviews three neutral open standards for facilitating MBD. These are ISO 103030 AP 242 for STEP AP 242 format, QIF 3.0 standard for QIF format, and ISO 14306 for JT format.

Feng et al. [7] presented EXPRESS data model in 1995 for representation of CAD models. This model is utilized in STEP by ISO 10303 Standard. However, the major issue with the EXPRESS model is it is not a well-known and well-developed language among developers to be used in applications programming interfaces (APIs) [19]. This shortcoming resulted in a

Feature Based	Assemblies with movable joints	Only rigid parts	1D propagation at time	Screw theory-based	Utilized in industrial scales for complex assemblies
• TTRS • Jacobian-torsor • T-Map and deviation domain • GapSpace	• Vector loop • TTRS • Jacobian-torsor • T-Map and deviation domain • GapSpace	• TTRS • Jacobian-torsor • T-Map and deviation domain • Vector loop • GapSpace	• Vector loop • TTRS • Deviation domain	• TTRS • Matrix • Jacobian-torsor	• Matrix • FEM based methods • T-Map
				Deviation space-based	**Used for less complex assemblies and simulations**
				• T-Map • Deviation domain	• TTRS • Vector loop
Point Based	**Welded assemblies with weld sequence**	**Both rigid and Compliant parts**	**3D variation propagation**	**Other bases**	**Not utilized in industrial scales**
• FEM based methods (including Skin shape) • Matrix • Vector loop	• Matrix • FEM based methods	• Matrix • FEM based methods	• Matrix • FEM based methods • Jacobian-torsor • Gap-based • T-Map and deviation domain	• FEM based method • Gap-based • Vector loop(kinematic based)	• Jacobian-torsor • Gap-based • Deviation domain

Fig. 2. Several criteria of categorizing tolerance analysis methods and how some models are placed in those categories.

demand for the development of extensible markup language (XML) based representation of PMIs [18]. In contrary to EXPRESS, XML is a general well-known format of data, and numerous tools and methods are developed to facilitate its utilization.

The data in XML format, are structured using tags. Each entity of data is represented by a tag. An entity can have children entities. Defining a standard data format based on XML means setting rules to define the valid tags, the parent/children relationships among tags, the minimum and maximum instances of each entity, and a handful of more checks. These rules are then written in XML schema definition (XSD) files where each XML file can be validated against them through a computer program. In addition, extensible style-sheet language transformations (XSLT) files are provided as well which do semantic connection check of data and reference checking among different file instances that refer to each-others elements. The XSD files can be converted to standard classes of other programming languages by utilizing code binding programs. This advantage makes these standards easy to utilize in different programs no matter in which programming language they are developed.

The utilized data model in STEP format has been EXPRESS language. ISO 103030 standard started integrating semantic PMI data mainly by introducing STEP AP 214. Nevertheless, the first edition of AP 242 that was introduced in 2014 had significant updates to import semantic integration of PMIs, kinematics, and tessellation. This version had capabilities of two previous versions of AP 203 which is aerospace focused and AP 214 which is automotive industry-focused. The second edition of AP 242 was released in 2020. This edition is shifted toward XML-based data structure and integration of semantic PMI is further improved. The capabilities of AP 209 and 210 which are composite and electronic focused, respectively, are also added to this edition [1].

Another extensive standard in this regard is QIF 3.0. QIF standard replaced the Dimensional Measuring Interface Standard (DMIS) from 2013. Compared with STEP AP 242, QIF is more metrology-focused. It includes the inspection results and statistics, and measurement planes, in addition to semantic PMIs and features. QIF is an open standard data model based on the XML format. A QIF file includes the geometry data in either mesh format or B-reps, topology data, measurement features, all GD&Ts, measurement plans, measurement data, and measurement statistics of the product. All these data are semantically connected and can be traced throughout the process. There is also the possibility of connecting these data to a CAD model and 2D drawings in either digital or hard copy format. However, there should be a persistence ID for the referred entities so that they can be traced back. The advantage of this standard is its capability to reduce manual work and errors, to facilitate a clear connection between inspection data and PMI, and to track all individual parts. On the other hand, the main disadvantage of it is not being utilized on an industrial scale so far.

The third open standard that is already in the use on an industrial scale, particularly by the automotive industry is ISO 14306 which represents the Jupiter Tessellation (JT) format files. This format was first developed by Engineering automation Inc around 2005. Then, it was bought by SIEMENS in 2007, and it became an ISO standard in 2010. The JT format is well-known for being lightweight for detailed visualizations and semantic PMIs. This advantage is gained by the compression techniques that are employed for its development. On the other hand, this format cannot be directly utilized in manufacturing processes and the inspection standards cannot be included in this format [27].

There have been several studies regarding data exchange among these formats or integrating them. Kwon et al. [12] developed a method for translation and utilization of data between QIF and STEP AP 242 by generating an OWL structure of each format. They summarize the advantages of that work as the possibility of checking the functional and geometrical requirements and tracing the requirements that may exist in the STEP format but not in the QIF. Katzenbach et al. [11] have suggested integration of JT format in STEP AP 242 for representing the CAD data and PMIs. Since STEP AP 242 is also XML-based, any CAD format can be used to represent the geometry.

4. Integration of MBD into CAT methods

Since every CAT method has its own capabilities and limitations, integration of MBD into CAT is highly dependent on the utilized CAT method. Based on the brief review of CAT methods in Section 2, there are numerous methods and models in CAT systems, some for only a portion of the procedure and several for the entire procedure. However, limiting them to methods that have been utilized in industrial scales, only a handful of them will remain. In the domain of fixed joint assemblies, the only promising methods so far have been FE-based and matrix methods. In the case of movable joint assemblies, there are still some unsolved complexities in most of the methods that hinder them from being common for use of an engineer without a deep knowledge of how the method works. In this application, there are only a few examples in the academic papers where a method is applied to a complex industrial-scale problem. The study by Ramnath et al. [22] is one of these examples, where the variation of one clearance in a gearbox is determined. A rough comparison of the scales of these problems evidences that FE-based methods are relatively ahead in solving industrial-scale problems. Using FE-based methods, variation propagation and sensitivity analysis of thousands of measurement points can be simulated even for a complete BIW or an airplane structure without requiring knowledge about FE and contact equations. On the other hand, simulating the variation propagation of only a clearance in a pump or a gearbox is still considered complex.

4.1. CAT automation

The main objective of utilizing MBD is to reduce the human work and dependency on humans in the processes to improve speed and lower errors. For some processes, the process itself will be removed e.g. generation of 2D drawings. For other processes, the processes will not be removed but will be performed by a computer instead of a human, including the CMM code writing or checking the measurement data for approval. Tolerance modeling and analysis will still be required, but MBD can help to reduce the effort of performing it or perform at least a portion of it automatically. Venkiteswaran [26] has developed a translator from STEP AP 242 to Constraint-Tolerance-Feature (CTF) graph models to use for automated tolerancing. The problems they have faced are mainly in the translation of some geometrical tolerances including Run-out, Profile, and datum targets which are not presented as a feature. A CTF graph is a representation data model, presented by Wu et al. [25].

An MBD model can include all data that a tolerancing engineer requires for tolerance analysis. These data include but are not limited to GD&Ts, datum definitions and datum reference frames, datum targets, the requirements, the manufacturing processes information, and the measurement tools and plans. However, it is not granted whether the availability of these data is sufficient for automating the entire CAD procedure or the extent to which a CAT procedure can be automated.

Considering the welded assemblies and FE-based methods, the inputs of simulations for such a method are the GD&T and datum data, but in nodes of a meshed geometry. However, the MBD models, particularly QIF 3.0 and STEP AP 242, present the PMIs semantically connected to features. These features can be defined independently, based on a geometry that its data is available either by a mesh file or B-Reps. Accordingly, there are no limitations about the type of data that are available in these formats. Consequently, if the features are defined based on nodes of mesh geometry, they can directly be used in an FE-based CAT system. But if they are based on another type of geometry or an external model, then a translation of data is required from feature-based GD&Ts to node deviations.

A crucial point in this regard is whether this translation can be performed without losing data. The main reason for utilizing GD&T instead of size tolerances is to describe the part geometry in a function-oriented base [14]. The geometrical tolerances, tolerance modifiers, datum precedence are all factors that affect the functional requirements of the product. Every deformation zone or shape can be described by the deviation of some nodes in a meshed geometry. However, a comprehensive method or tool for translating all GD&T parameters to define that deformed zone is a niche in this regard. It is not also clear if some parameters including datum precedence can be translated to some node deviations without losing data. Nevertheless, commonly in welded assemblies which are the domain of products for FE-based methods, datum targets are utilized instead of datum features and feature-based reference frames. The main geometrical tolerances are also commonly position and profile tolerances which can be simulated without a problem using node deviations.

Regarding the assemblies with movable joints, most geometric tolerances, different datum types, and datum precedence are directly considered in most of the methods. Therefore, there are fewer complexities to receiving the input data from an MBD model by these methods. The main issue can be the lack of data that these methods require for automation that lacks in MBD models e.g. kinematic constraints of an assembly.

4.2. Integration of measurement data into CAT

Another benefit of MBD models in the context of CAT is the integration of inspection data into tolerance analysis. This is not a new ability to be provided by MBD but MBD facilitates automation of this process and reduces the efforts and costs associated with it.

QIF 3.0 can include all inspection data of products, in which each measurement is connected semantically to its relative characteristics and feature. Moreover, requirement fulfillment statutes of each measurement and all statistics related to that can be stored in and retrieved from a QIF file. These data can be utilized for determining the part variations' distributions, as an input to variation simulation of the assemblies. This is particularly important in FE-based methods to determine the form deformations in non-rigid simulations. Having this information is critical in these simulations and it is challenging to estimate them if measurement data are not available [23]. The CAT methods for movable assemblies can also benefit in the same manner from these data. For instance, in the T-Map method, the hypothetical deviation space is determined either by considering the maximum deviations possible based on defined GD&Ts (worst-case) or by considering normally distributed deviations for the feature. Accordingly, substituting the estimated values with measured values may increase the accuracy of the analysis.

4.3. Challenges

Employing MBD and integrating it to CAT methods though beneficial in general, is challenging as well. A challenge that is common in most paradigm shifts, is the inertia of the system against changes. 2D drawings and utilization of different data sources from different resource models have been for a long time the dominant method of production and it is quite established now. Shifting from such an established method may require a huge investment before starting to return benefits. In addition, the existing data and models are all in other formats. Consequently, moving to a new modeling format and paradigm may require remodeling all previous models or having two different paradigms running in parallel. None of these scenarios is desired by manufacturers unless the benefits they will receive in long term overcome these costs.

Another challenge comes from the integration of data to CAD methods itself. Not every CAT method can handle every type of simulation, and not all CAT methods can handle every GD&T characteristic. For instance, there is not an established method to translate the datum precedence and material modifiers in FE-based and Vector loop methods. Consequently, one method or tool would not be able to automatically receive an MBD model and conduct all the analyses. Hence, both limitations of the CAT method and data included in the MBD are required to be known and matched before the utilization of a method. This matching process can be a hindrance in CAT automation.

4.4. Future works

The integration of MBD models in CAT methods is a quite intact research subject. There is a niche in the available methods and tools for this integration, particularly in the translation of GD&T into representation models that can be utilized in a CAT analysis method directly. Moreover, there can be several challenges and problems that emerge when a practical integration starts on an industrial scale. Therefore, an important demand in this context is the implementation of MBDs in CAT processes as case studies to evaluate the gains and challenges.

5. Summary

A review of MBD open standards and their integration into CAT methods was presented in this study. EXPRESS is the most common data model for representing the CAD data and GD&Ts. Also, the most common methods of tolerance analysis based on their utilization in industrial-scale problems and common commercial programs are: FE-based methods, T-Maps and Vector loops. Two main opportunities in integrating MBD in CAT methods and tools are automation of the CAT modeling and processes and integration of inspection data in CAT analysis. The main challenge regarding this integration is moving from already established methods to the new methods and translating the MBD data to the required format of data for each tolerance analysis method.

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