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On the potential of the Quality Information Framework (QIF) standard driving the interoperability in variation simulation

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ABSTRACT: Variation simulation approaches are frequently used to analyse the effects of geometrical variations on the final product quality. Various software tools are used during product development as they strongly differ in their specified goals, the context of use, and users. Although a few workarounds and information-sharing strategies exist, switching software usually results in the simulation model being built from scratch, leading to redundant manual effort and uncertainties. This paper examines the potential and limitations of the Quality Information Framework (QIF) information model in improving collaborative work within a heterogeneous simulation software landscape by exchanging variation simulation model-related information in a standardised Model-Based Definition sense. An application scenario shows how QIF can bridge the gap between tools used in early and late design phases.

KEYWORDS: tolerance representation and management, robust design, simulation, quality information framework (QIF), geometry assurance

1. Motivation

Product design is a complex and highly challenging task. All needs and expectations must be transformed into a single product, which must be well-engineered to be competitive in tough international markets (Isaksson & Eckert, 2020). For its success, high product quality is decisive and expressed through various characteristics, such as reliability, performance, or perceived quality (Garvin, 1988). The part geometries and the assembly design are crucial in achieving these goals (Söderberg et al., 2006). From a technical and cost perspective, unavoidable geometry variation is a challenge since it significantly mitigates product quality (Morse et al., 2018). For this reason, minimising the effect of geometrical variation in the final product is essential and is focused by numerous geometry assurance activities throughout the entire product development process (Söderberg et al., 2016). Referring to this year's conference theme, geometry assurance can be seen as a team sport that includes numerous people from different divisions, particularly product design, manufacturing, and inspection. Typically, they rely on simulation to analyse the effect of manufacturing-induced variations and virtually ensure product quality at an early stage (Söderberg et al., 2016). Multiple different software tools are commonly used in this multi-stage, iterative process to assure the quality of one mutual product. A high degree of software interoperability favours the collaborative work of all parties involved, as otherwise, information must be transferred manually, and models must be partially or entirely rebuilt, leading to additional time effort and model uncertainties. Hence, this article studies the current state of the interoperability of variation simulation tools and the potential of the Quality Information Framework (QIF) standard for improvement.

2. State of the art

To reflect the current state of the art, Section 2.1 examines the diversity of variation simulation software used for geometry assurance. Section 2.2 follows to present current strategies for shifting simulation models and information from one software tool to another, leading to this article's research question.

2.1. The diversity of variation simulation and its software tools

Variability is given in each manufacturing process and primarily depends on the materials and the process design, including the chosen equipment, i.e., the machines, tools, and fixtures (Singh et al., 2009). This leads to deviations of a single part geometry in its functional relevant portions, i.e. its features, and to variations observed for multiple parts manufactured with the same process (Wärmefjord et al., 2023). Hence, tolerances are specified in the design phase to communicate how much part variation is acceptable from an assembly quality point of view (Morse et al., 2018). Tolerance analysis is a helpful instrument for verifying whether the defined tolerance limits can fulfil predefined product quality requirements expressed by a set of representative Key Characteristics (KC) (Hong & Chang, 2002; Thornton, 1999). Hence, the terms 'variation simulation/variational analysis' and 'tolerance simulation/analysis' exist in parallel. The more general term 'variation simulation' is preferred in this article.

With the first computers being available in the middle of the last century, it was finally possible to implement the mathematically elaborated methods for statistical tolerance analysis (Walter, 2019). While early research works in this field date back to the 1960s (Walter, 2019), the first commercial software tools, primarily designed for tolerance analysis, were released in the 1990s (Prisco & Giorleo, 2002). The term 'Computer-Aided Tolerancing (CAT)' emerged during these times, emphasising the strong computerisation of the different tolerance design activities, including tolerance specification, allocation, analysis, and synthesis. At the same time, variation simulation has gradually established itself in manufacturing process planning at part and assembly levels (Hong & Chang, 2002). After more than half a decade of research and remarkable increases in computer performance, various software tools for variation simulation are frequently used throughout today's geometry assurance process. They can be roughly divided into two groups. First, there is specialised software for variation simulation, primarily but not only for statistically predicting the assembly responses to the part variations and identifying the main contributors to it (Söderberg et al., 2016). The tools are directly integrated into a Computer-Aided Design (CAD) environment or stand-alone (Cao et al., 2018). In addition to well-established commercial tools, prototypically implemented software is frequently used in research. Second, software, either used for general purposes, e.g., spreadsheets (Glancy et al., 1999), or used for virtual product development, e.g., for CAD (Goetz et al., 2018), Finite Element Analysis (Nerenst et al., 2021), Computational Fluid Dynamics (Lyu et al., 2006) or Virtual Reality (Wickman & Söderberg, 2007), are empowered to perform variation simulation and visualise the results.

When choosing a software tool for variation simulation, usability plays a decisive role (Glancy et al., 1999). According to ISO 9241-11, the term is generally defined as:

> *"the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (International Organization for Standardization, 2018, p. 6)*

Thus, the usability of variation simulation depends on the *specified users*, *goals*, and *context of use*.

Diversity of specified context of use

Due to the scope of the geometry assurance process, variation simulation is used both in very early and late design and all subsequent manufacturing-driven phases (Söderberg et al., 2016), resulting in different degrees of detail (first concepts vs. fully detailed products) and levels of consideration (product vs. process). The assembly type plays a decisive role, either purely through the assembly of the individual components or through additional process steps such as welding or riveting (Lupuleac et al., 2024). In addition, the product type, its behaviour, and the nature of the KCs define the context of use (Hallmann et al., 2020).

Diversity of specified goals

The shared objective of high product quality is expressed by and related to different sub-goals and constraints, e.g., robustness, functionality, assemblability, or costs. Variation simulation is used here for rough evaluations, detailed analyses, or optimisations, considering different viewpoints continuously changing over the product lifecycle process (Hong & Chang, 2002). It is, for example, used to evaluate the robustness of a product concept (Goetz et al., 2020) but also to optimise the manufacturing process, e.g., the fixture layout or joining sequence (Söderberg et al., 2016).

Diversity of specified users

The geometry assurance process covers product design-, process design-, and inspection-driven activities (Nickolaisen, 1999). Hence, variation simulation is used not only by tolerance specialists but also by product design, process design, and inspection engineers with different backgrounds and skills.
For these reasons, a single closed-loop software solution with high usability for the whole geometry assurance process is not given (Sigurdarson et al., 2018). Although it would be beneficial and support collaborative work, it may also realistically work only within a small, defined scale and very stringent product development processes. Heterogeneous software landscapes are common in practice, including numerous tools differing in their interpretations and prioritisation of *efficiency* and *effectiveness*, and thus different capabilities, modelling and analysis strategies, as well as data and information structures.

2.2. Strategies for collaborative work with multiple variation simulation software

When switching between variation simulation software, it is very likely that the mathematical models are different (Prisco & Giorleo, 2002). Automated model translation by bidirectional interfaces would be helpful but usually does not exist - even among the leading commercial tools for variation simulation software. A manual rebuilding of the entire model in a new software system from scratch is usual. Nevertheless, the modelling step can partially be automated using the geometry and specification information semantically given in the CAD model (Haghighi et al., 2019). If variation simulation is not directly embedded in a CAD tool, the STEP AP242 and JT formats are often used as neutral derivatives (Hallmann et al., 2019). They support the philosophy of Model-Based Definition (MBD), bridging the information gap between CAD and CAT systems (Aderiani et al., 2022) while, in general, supporting communication and collaborative work (Camba et al., 2014; Lenne et al., 2009). As they are limited in their scope on product and manufacturing information (PMI), specific information models (Qin et al., 2018) and information-sharing workflows (Schleich & Anwer, 2021) have been proposed in the literature. Due to its focus on quality management, the QIF format has recently drawn attention to fostering MBD in variation simulation (Aderiani et al., 2022; Schleich & Anwer, 2021; Roth et al., 2025). The first CAD systems offer a direct QIF export (Autodesk Inc., 2024), and third-party translators exist (Capvidia, 2024). However, it has not yet been considered for CAT environments. Thus, the interoperability of variation simulation tools is still limited. Besides additional manual effort, it leads to format and information gaps, model uncertainties, and thus, limited comparability of results, and makes collaborative work difficult.
Hence, this article focuses on the research question of *whether and to what extent neutral file formats, in particular QIF, can enhance interoperability between variation simulation tools.*

3. Linking variation simulation software with the QIF format

The reflection on the related works in Section 2.1 emphasised the software diversity for variation simulation. Nonetheless, they typically are based on two sub-models to mimic a product under variations. The geometrical model is used to represent the nominal part geometry, described in terms of features or characteristics and their deviated status, using tolerance specification or variation information (Dumas et al., 2015). A second model is needed to propagate the part variations on the assembly level through their mating features while considering additional variations originating from the assembly process (Dumas et al., 2015). Using both models jointly, the assemblies in their deviated states can be simulated. Sampling methods, such as Monte Carlo Sampling, are typically used to probabilistically map production variability through a finite number of representative samples (Morse et al., 2018). They serve as the basis for investigating how the assembly responds to the variations (Hong & Chang, 2002). In literature, the term assembly behaviour model is commonly used to describe a model that accumulates deviations on the assembly level and directly outputs the assembly response (Morse et al., 2018). However, it is crucial to understand that simulating the assembly behaviour implies representing the product after assembly and further establishing the relation to the variable to be evaluated, which may require further models, depending on the nature of the assembly response and the purpose of the simulation model. Instead of first generating and second propagating the part deviations on the assembly level, it is also possible to directly map tolerances into subsets of multidimensional hyperspaces and accumulate them through mathematical set operations (Dantan et al., 2012). However, deviation accumulation approaches are more established than tolerance accumulation approaches and are the basis of most variation simulation tools.

Since the motivation to use variation simulation can vary greatly, multiple software tools are typically used to develop one mutual product (see Section 2.1). Hence, there are one or several reasons for switching software. On the one hand, it can be motivated from an organisational point of view, such as by license availability or external demands. On the other hand, there are strategic reasons from a simulation point of view, which can be traced back to four main motivations, illustrated in Figure 1.

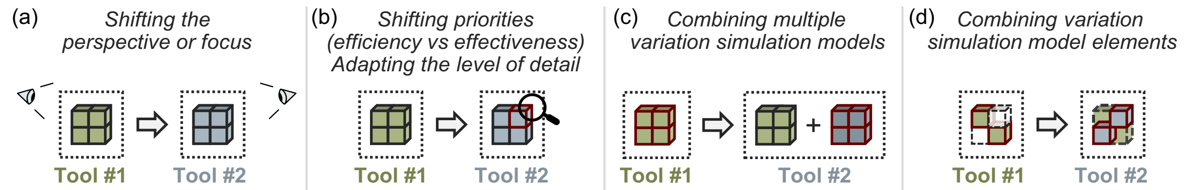

Figure 1. Motivations for switching variation simulation tools within the geometry assurance

First, the *perspective or focus of variation simulation* can shift when the goal or the context of use changes (see Figure 1 (a)). For example, an optimal joining and clamping sequence should be identified using tool #2 after a robust datum system is identified in tool #1 in an early design stage.

Second, the *prioritisation of efficiency and effectiveness*, i.e., the accuracy and completeness of a tool (International Organization for Standardization, 2018), might be shifted (see Figure 1 (b)). While more approximative but fast models are helpful for initial evaluations, e.g. to study multiple design alternatives, adapting the level of detail of some parts of the model is needed to increase the simulation's effectiveness. This can either be of interest for the entire simulation scope or only partially, such as for critical states in adjustable and time-variant systems or for verifying virtually identified part instance combinations, which lead to KC values close to quality-critical specification limits. Examples include realistic modelling of the part's assembly process, physical phenomena such as non-rigidity or residual stresses, or shape deviations.

The more comprehensive and complex a product is, the more critical it is to break it down into suitable sub-assemblies and build a simulation model for each separately. In this case, the exchange of information between the models at their interfaces becomes decisive. As they are not necessarily defined in the same software tool, it leads to the third motivation. For example, the output of one simulation to investigate the function-critical features of riveted assemblies can serve as input for a subsequent FEA to investigate the part variations' effects after assembly on the mechanical properties. In this way, two complete *variation simulations are used in combination* (see Figure 1 (c)).

Fourth, and similar to third, *combining several model elements* from different software tools can make sense to exploit their capabilities (see Figure 1 (d)). For example, the part variations are first simulated using a software tool showing strengths in the ISO or ASME standard-compliant mapping of geometric tolerances or manufacturing-specific characteristics through probabilistic simulation of the part manufacturing process, such as casting or injection moulding. Second, they are combined with software to represent the assembly process realistically.

Though there are already numerous reasons to switch software tools, the variety of mathematical models used further complicates their practical realisation and requires model translations. As well-known from collaborative work with multiple CAD software, ensuring the interoperability of all n tools, a directional, two-way model-to-model translation requires $N = n!/(2!\cdot(n-2)!)$ interfaces (Marjudi et al., 2010). Figure 2 exemplifies this issue for a few variation simulation tools. Neutral exchange formats reduce the number to n, but their scope limits the information for the indirect model translation. STEP AP242 and JT are often preferred to establish the link between CAD and variation simulation tools, exchanging the part's geometry and semantic GD&T information. So, if a neutral format should benefit from linking variation simulation tools, it must be able to represent information beyond the one given in an initial CAD model used as a starting point.

STEP AP242, JT and QIF 3.0 are the three main MBD-supporting formats that can semantically link the Geometric Dimensioning and Tolerancing (GD&T) specification, annotated in CAD, to the referenced geometrical features. All three use Boundary Representation (BREP) elements to describe the part's topology and geometry, supporting the idea of a parametric feature-based description. While overlapping in the MBD information model with STEP AP242 (Kwon et al., 2020) and JT, QIF shows some strengths for its use within the given context.

First, it allows a structured hybrid representation of multiple topologies within one file, such as point cloud, wire, parametric and mesh elements, defining the "boundaries of geometry objects and specify[ing] connectivity relations" (International Organization for Standardization, 2020, p. 243). Figure 3 illustrates different topologies with their geometry elements, e.g., meshed or parametric surfaces, curves and points, describing a cylindrical feature in the 3D space.

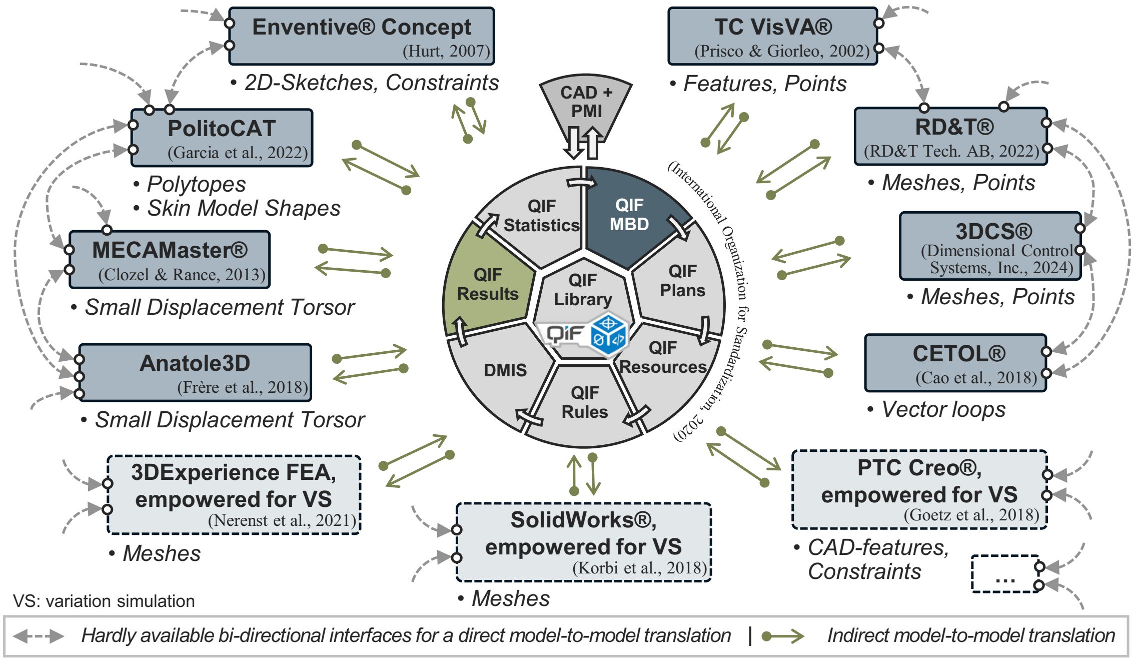

Figure 2. General idea of an indirect variation model-to-variation model mapping via QIF

Second, QIF is designed to add further information models (see Figure 2, centre) to support the part inspection process and store the results in an MBD way in one single file. The as-designed and the as-inspected status for multiple part instances are linked through *Features* and *Characteristics*, representing annotated GD&T information (see Figure 3, centre). In addition to real measurement information, it is possible to use these elements to map the virtually generated features in simulation with their individual deviations, corresponding to the virtual as-inspected status of the parts expressed either by *CharacteristicMeasurement*, *FeatureMeasurement*, or *MeasuredPointSet* elements using so-called identification designators (id). They are unique integer values assigned to each QIF element and used as references to create semantic relations between all the individual elements, for instance, to point from one *FeatureMeasurement* on the underlying measurement point list given in a separate *MeasuredPointSet* element. This benefit makes QIF particularly attractive for applications in the geometry assurance context compared to STEP AP242 and JT. Thus, the QIF scope and structure can map all information needed to set up the geometrical model for deviation accumulation approaches, viz. nominal part geometry, GD&T and variation information. However, the information has always to be translated into the QIF language restricted to the elements describing topology, geometry and measurement results (Figure 3). Since tolerance accumulation approaches like Polytopes or T-Maps® do not use variation information, information exchange via QIF is limited.

Moreover, since the QIF format is part-oriented, relations between the parts, e.g., assembly constraints, which are necessary for the analysis on the assembly level, cannot be mapped with QIF (International Organization for Standardization, 2020). Hence, storing variation simulation information from the assembly level is highly limited. For more details about the structure and XML-based syntax of QIF, please refer to (International Organization for Standardization, 2020); for a graphical illustration, to (Roth et al., 2025).

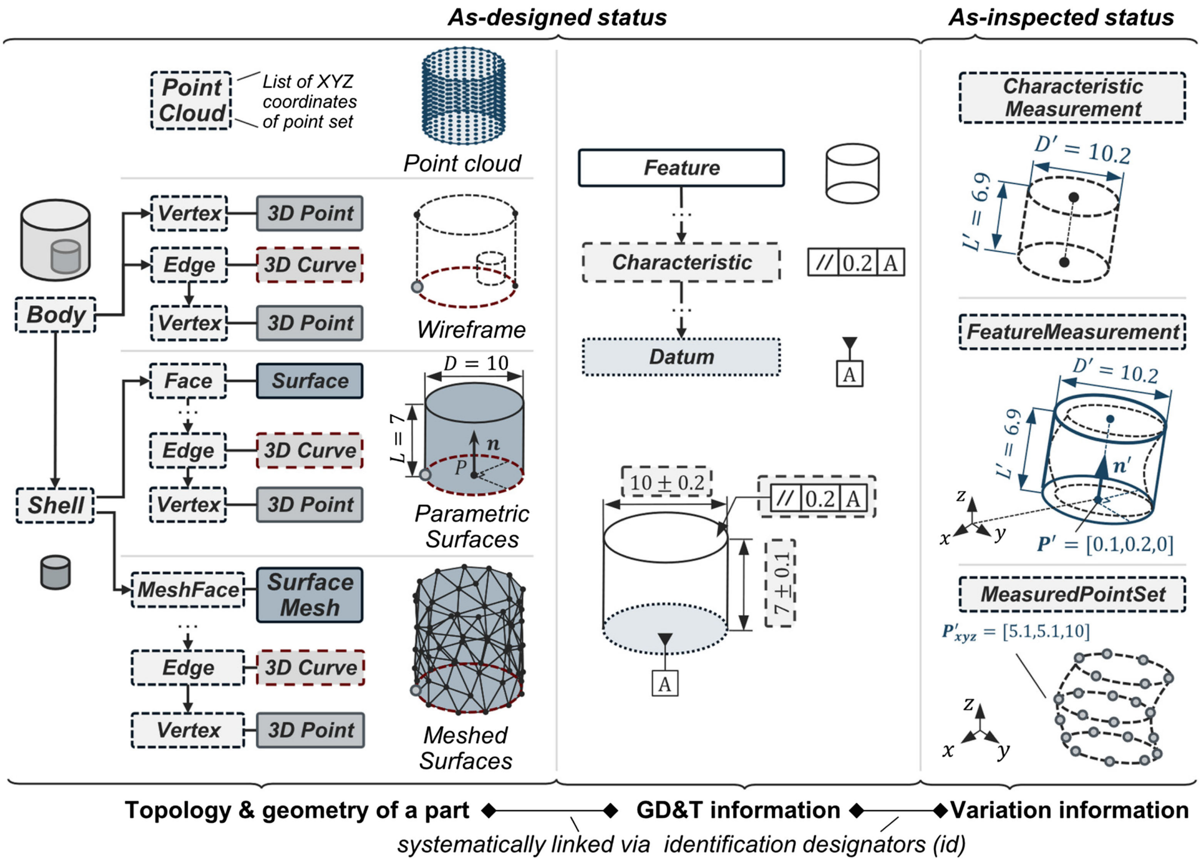

Figure 3. QIF-information elements relevant for variation simulation model information exchange

4. Application and discussion of the proposed solution approach

The previous section proposed linking different variation simulation tools via QIF from a conceptual point of view. This section presents a practical example of a collaborative work scenario for virtually assuring the geometry of a skateboard truck. The focus is on the general information flow between the involved tools and QIF; details on the simulation and results are not further addressed.

4.1. Application scenario

Figure 4 illustrates that variation simulation is already used in the early phases for first concept evaluations directly in the CAD environment, here Autodesk Inventor ®Professional 2025. Since the design is typically not detailed in this phase, the product designer uses only the functionally relevant features, represented via general CAD features, such as cylinders or planes, enriched with semantic GD&T annotations. These features are CAD-internally varied, e.g., through dimension changes or available modification operations such as offset or tilting. Similar to the procedure in (Goetz et al., 2018), the various virtual product instances are varied via controlled parameters, in this case via the iParts and iLogic functions, and the part constraints in the assembly are automatically updated. Based on the resulting assembly with deviations, the assembly response is evaluated using CAD-internal measurement operations, in this case, an angle measurement between the hanger axis and the baseplate plane. Only information from the geometrical model is translated into QIF after simulation due to its limitations in representing assembly-related information described in Section 3. Figure 4 (1) exemplifies the translation of the nominal CAD geometry with PMIs and variation information of a few features of the truck's hanger and base plate. The individually generated CAD features are stored in the QIF files as *FeatureMeasurement* elements according to their geometry type and semantically linked with the nominal geometry (via *Features* and *Characteristics* elements, see Figure 3).

When the focus shifts to assuring the final design, the actual manufacturing conditions must be considered in variation simulation. In this example, the numerical process simulation esi ProCAST ™ helps mimic the probabilistic character of the gravity casting of the hanger with a moulded axle (see Figure 4 (2a)). By systematically perturbing the mould and gating system geometry and the process parameters sensitive to the geometry, such as mould and pouring temperature or cooling rate, the process

simulation engineer obtains systematic and random part variation information as input for the subsequent simulation on the assembly level (Lorin et al., 2012). For each casting result, represented by a triangulated surface mesh, the respective QIF features are associated with the relevant feature triangles and appended to the existing QIF file as individual *FeatureMeasurement* elements. Adding the mesh points as a list of virtual measurement points structured within a *MeasuredPointSet* element allows the model to be augmented with discrete point-based representation information. In doing so, the approximates from the early phase for the hanger can be substituted.
Jointly with the sufficiently accurate information from the early phase for the milled baseplate, they are used by the tolerance engineer to automatically rebuild the geometrical model in a more advanced CAT tool, in this case, RD&T ®. Therefore, the parametric QIF feature information from the early phase must be translated into a point-based representation (see Figure 4 (2b)), while the measured points from the process simulation can be used directly. Details on applicable mapping strategies can be found in (Roth et al., 2024). The part positioning and measurement operations cannot be mapped via QIF (see Section 3) and must be assigned manually before variation simulation is performed in this phase.

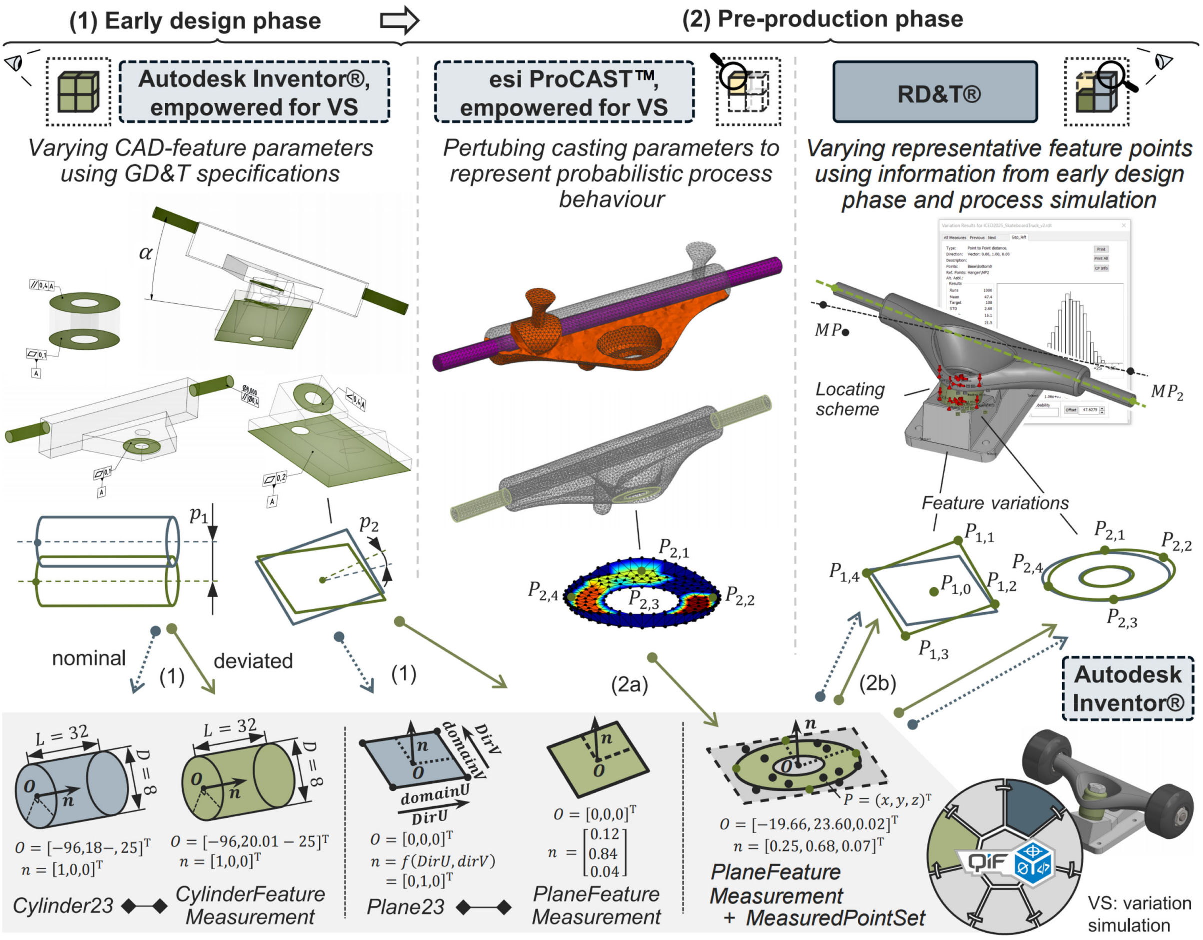

Figure 4. Collaborative variation simulation scenario covering three perspectives, users and software tools for the geometry assurance of a skateboard truck assembly used as a case study

4.2. Discussion on its strengths and limitations

The application scenario illustrates that the indirect model translation via QIF is beneficial for increasing the level of automation by transferring the information of deviating geometry between different tools. QIF's nature as a hybrid representation model (see Figure 3) enables the representation of the part's geometry in multiple forms. It semantically links it to the GD&T specification information in compliance with ISO and ASME standards. Especially in the early design stages, the semantic GD&T information helps to generate variation information on the part level automatically. Appending the virtual 'as-inspected' parts helps carry the variation information virtually generated in simulation. Similar to the nominal status, it is flexible since it can be represented as single-value characteristics, parametric features, or discrete points. Hence, it can cover the scope of the geometrical model on the part level. Even if it cannot replicate a fully controllable geometrical model, it makes its remodelling obsolete by directly providing all the information. Further, it offers the possibility of infusing the variation models with real inspection information. The case study exemplified that it facilitates combining models while adapting the level of detail for different activities within the geometry assurance while shifting the perspective (see Figure 1 (a-c)). Compared to manual modelling and transforming the model, it improves consistency, lowers the risk of manual modelling errors and avoids ambiguity through the standardised QIF structure. Exchanging the variation information for all features further reduces uncertainties resulting from the randomness of probabilistic sampling (Roth et al., 2022). Thus, it fosters the comparability of variation simulation results obtained with different tools.

The size of the QIF files significantly increases with the number of features and the chosen sample size. More complex problems than the highlighted scenario, for instance, mega-casted parts, can cover many functional-relevant features that do not necessarily result from one manufacturing process (Wärmefjord et al., 2023). If large amounts of data and larger file sizes are acceptable, exchanging variation simulation information across different manufacturing stages via QIF can be beneficial to capture and communicate the intermediate geometry states, e.g., after the casting and subsequent machining steps. Thus, it can further support the reuse of previous simulation information in the early phases of a new product generation (Roth et al., 2024). The overall premise is that suitable strategies for mapping from and to QIF are developed. However, open-source code available in C++, C#, and Python and a comprehensive documentation webpage support a straightforward implementation of QIF reading and writing functionalities (Campbell et al., 2019; QIF Community, 2024).

Nevertheless, using QIF files as a standardised information carrier comes at a price. Due to its restrictions in scope, representing information for the assembly behaviour model is highly limited. Except for the nominal part's orientation and location, no suitable elements are available to define assembly constraints, fixture layouts, etc. Information losses are unavoidable if the assembly behaviour model information is not stored outside of QIF, for instance, in an ontology, as Lu et al. (2015) introduced. Combining ontologies and QIF, as proposed in (Kwon et al., 2020) and proven beneficial for STEP (Barbau et al., 2012), provides a promising way to augment the neutral model with additional information. This also includes non-geometrical information, such as on physical phenomena like residual stresses, e.g., typically restrained in mega-casted parts and affecting the assembly quality (Wärmefjord et al., 2023). Besides the challenge of defining an information model in a standardised way, the different methods for propagating the variations on the assembly level, e.g., by contact modelling, rigid body transformations or constraint modelling, complicate finding a generic information model structure. Besides, changes in dimensionality, such as from 2D to 3D, as well as significant differences in the level of detail throughout the product development process, such as wireframe models in early phases and detailed, discrete geometry simulation in late phases, represent a challenge for an automatic model translation and must be studied for their potential.

5. Conclusion

Variation simulation is performed using different software to analyse the influence of geometrical variations on product quality. The QIF standard provides a promising solution to bridge gaps between software tools since it can store the nominal as-designed status of the parts and the virtually generated part instances with its feature variations. Despite its strengths on the part level, most information on the assembly level cannot be represented within QIF, hindering a complete automated model translation.

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