applied sciences

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Tolerancing Informatics: Towards Automatic Tolerancing Information Processing in Geometrical Variations Management

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Abstract: The management of geometrical variations throughout the product life cycle strongly relies on the gathering, processing, sharing and dissemination of tolerancing information and knowledge. While today, this is performed with many manual interventions, new means for automatic information processing are required in future geometrical variations management to make full use of new digitalization paradigms, such as industry 4.0 and digital twins. To achieve this, the paper proposes the term tolerancing informatics and investigates new concepts and means for automatic information processing, novel information sharing workflows as well as the integration of tools for next generation geometrical variations management. In this regard, the main aim of the paper is to structure existing tolerancing informatics workflows as well as to derive future research potentials and challenges in this domain. The novelty of the paper can be found in providing a comprehensive overview of tolerancing informatics as an important enabler for future geometrical variations management.

Keywords: tolerancing; information; design

Citation: Schleich, B.; Anwer, N. Tolerancing Informatics: Towards Automatic Tolerancing Information Processing in Geometrical Variations Management. *Appl. Sci.* **2021**, *11*, 198. https://doi.org/10.3390/app11010198

Received: 7 December 2020
Accepted: 24 December 2020
Published: 28 December 2020

1. Introduction

For technical and economic reasons, geometrical deviations are inevitably observed on every manufactured artefact. Since they have serious effects on the function and quality of complex products, there is an important need for geometrical variations management, which covers all efforts related to controlling and minimizing the effects of geometrical part deviations on the product quality [1]. Typically, this involves the assignment of tolerance limits ("tolerances") to geometrical part features during product design, which are communicated to all downstream activities. Tolerancing is thus understood as the set of activities which manage the tolerances during the product development [2]. Hence, the management of geometrical variations strongly relies on the gathering, processing, sharing and dissemination of tolerancing information and knowledge. Today, this is performed with many manual interventions and new means for automatic information processing are required to fully exploit new digitalization paradigms introduced by the digital transformation in design and manufacturing, such as industry 4.0, cyber-physical (production) systems and digital twins. However, while current research efforts only focus on specific sub-aspects of this problem, such as the authoring of tolerancing information or representation models for tolerancing information, there is a lack of a comprehensive and holistic study on the main benefits and future potentials of automatic tolerancing information processing. Motivated by this lack, this paper proposes the term "tolerancing informatics" and investigates new means for automatic information processing and novel information sharing workflows for geometrical variations management of the future.

2. State of the Art: Tolerancing Information Sharing throughout the Product Life Cycle

2.1. The Role of Tolerancing Information

The main goal of all product development activities is the provision of products that live up to the customer requirements. In this context, tolerancing for design or functional tolerancing can be defined as the set of all design activities that aim at translating such functional (customer) requirements (FR) into geometrical specifications of the single parts, which is relevant even at the early design stages [3,4]. More particularly, this involves tolerance specification, i.e., identifying required tolerance types on function-relevant features as well as suitable datum features, tolerance allocation (i.e., defining suitable values for these tolerance types), and tolerance analysis (i.e., the evaluation if the chosen tolerance types and values ensure the functional requirements) [5]. As a result, these geometrical specifications are typically annotated during design and presented as symbols and numerical quantities on technical drawings or on three-dimensional solid models and represented per semantic model-based definition (MBD) of product and manufacturing information (PMI) [6]. In this regard, the concept of tolerancing evolved from the need for the unambiguous communication between the various actors in geometrical variations management. However, this communication is not unidirectional from design to manufacturing and inspection activities. However, as tolerances link the design intent and the product function with the manufacturing capability and measurement accuracy [2], they serve as a multi-directional connection and are means to overcome the disruption of the different activities in geometrical variations management and to reintegrate them by knowledge and information sharing [7]. Consequently, tolerances affect nearly every aspect of the product origination (see Figure 1) and they are required by many actors for different purposes, e.g., for tolerance transfer, tolerance synthesis, tolerance verification and performance correlation [8]. In this regard, tolerances are a critical link between design, manufacturing, inspection and assembly as they have distinct effects on the product function and quality as well as on the manufacturing, inspection and assembly costs.

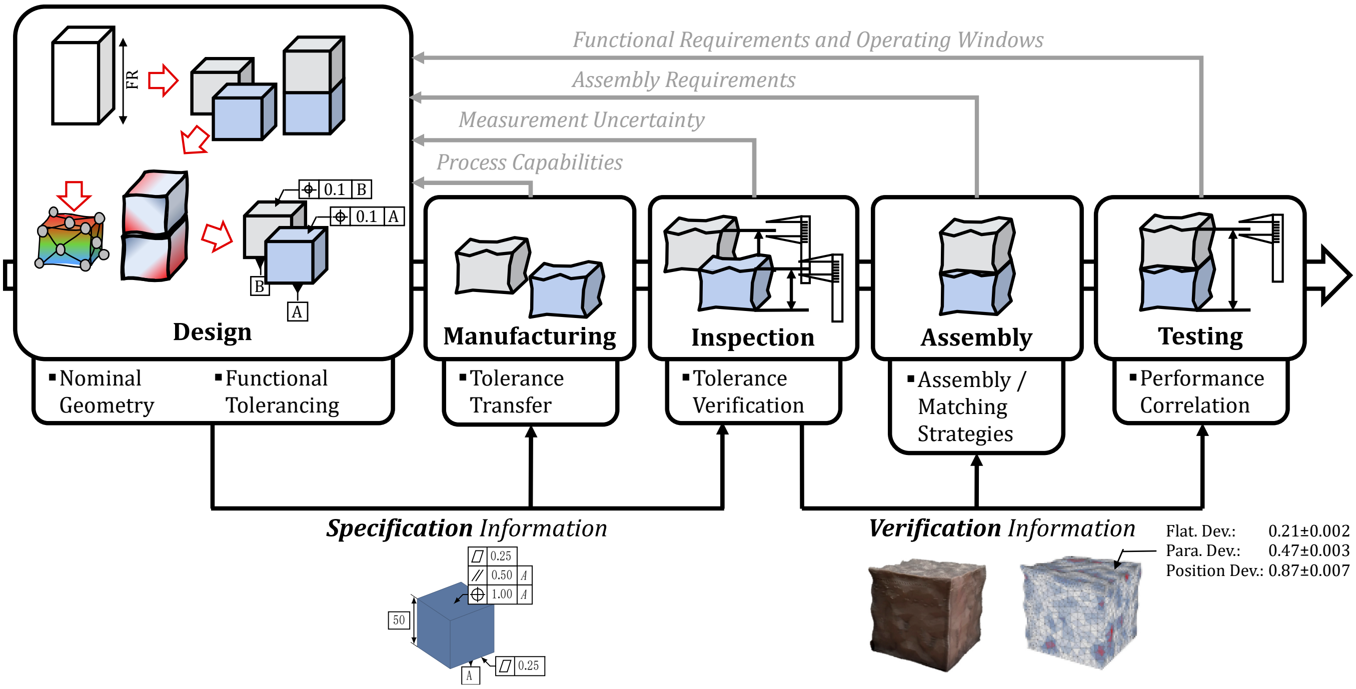

Figure 1. The ubiquitous role of tolerances and different types of tolerancing information. FR: functional (customer) requirements.

2.2. Types of Tolerancing Information

Based on Figure 1, it can be seen that different kinds of tolerancing information exist throughout the product life cycle. While the nominal product geometry and the specified tolerances are relevant during the design and manufacturing planning stages, part inspection processes add information about the observed part geometry and the process capability. Consequently, it is reasonable to divide the set of tolerancing information in specification information and verification information:

- Specification information results as in- and output of functional tolerancing during design, i.e., nominal product geometry, functional product requirements, geometrical product requirements, tolerance types and specified tolerance values. More particularly, it is distinguished in ISO 21619 between functional specifications, which result from functional product requirements, manufacturing specifications, which are to satisfy requirements of related manufacturing processes, and verification specifications.
- Verification information is obtained from verification activities, such as the observed part geometry, observed tolerance values, and the measurement uncertainty related to the tolerance verification. Beside the information about the conformance of the individual part instances to the specifications and the actual part deviations, it comprises information about the measurement processes and their uncertainties.

These two distinct categories of tolerancing information can also be enriched by manufacturing, inspection and assembly process data leading to insights on how the process parameters relate to the geometrical part or assembly characteristics.

2.3. Authoring of Tolerancing Information

Considering the authoring of (specification-related) tolerancing information, industry is gradually moving towards the model-based definition (MBD) of product manufacturing information (PMI) in three-dimensional part views of computer-aided design models, which is supported by most commercial computer-aided design tools. Today, this is partly supported by tools for rule-based tolerance specification, which allow checking for proper syntax and semantics of tolerance specifications regarding tolerancing standards, and tolerance analysis tools, which are to evaluate if the specified tolerances ensure the fulfilment of functional requirements. In this context, an overview of the current state of model-based definition can be found in [9], where it is concluded that further development, particularly considering the automatic information processing, is required to fully exploit the benefits of model-based definition practices.

2.4. Representation Models for Tolerancing Information

The efficient modelling and representation of tolerancing information has been identified as an important enabler for the seamless integration of tolerancing tasks in the virtual product development process. In this regard, a dimension and tolerance data model has been proposed in [10], which is to allow the communication between tolerance-related software tools. In the course of this, a layered tolerance representation model was proposed in [11] and the need for integrating tolerancing information in product life cycle management tools to allow tolerancing data traceability led to a functional architecture for tolerancing data in [12]. More recently, OWL-based (Web Ontology Language) domain ontology models for the representation of tolerancing information were proposed. Summarizing these research works, an in-depth analysis of existing representation models for tolerance information is provided in [13], concluding that future research is required regarding the automatic update of tolerance information representation models and the integration of these models into commercial computer-aided design tools.

2.5. Discussion

As a synthesis, though different tolerancing information representation models have been proposed in the literature, their application in current tolerancing information authoring (i.e., computer-aided design) and consumption tools (i.e., computer-aided manufacturing or computer-aided inspection) is lacking. Thus, these different approaches and tools are isolated applications that support specific geometrical variation management activities. However, up to now the available tools and solutions require many manual efforts and interventions regarding the authoring and processing of tolerancing information and knowledge. In contrast to that, fostered by advancements in information and communication technology, the automatic processing of tolerancing information is expected to gain increasing attention in research and industry. Moreover, the ongoing digitalization of design and manufacturing offer important potentials for linking the different tolerancing tasks with automated information processing workflows. Considering this research gap, the main research question is how future digitized geometrical variations management workflows could be shaped and which research efforts are required to allow their implementation. Motivated by this, we thus propose a definition for the term "tolerancing informatics" and sketch applications as well as benefits for automated tolerancing information processing workflows.

3. Tolerancing Informatics

3.1. Methodology

In order to provide an answer to the aforementioned research question, first a definition of the term tolerancing informatics is given. After that, the core enablers of tolerancing informatics are introduced and the most important tolerancing informatics workflows are detailed. Finally, a critical discussion and study limitations are presented.

3.2. Definition of Tolerancing Informatics

As it has been emphasized by many theoretical and practical works, a main challenge in geometrical variations management is the moderation of information and knowledge exchange processes in small and especially in large value chains with multiple actors in the same or even different companies. In this regard, many different pieces of tolerancing information must be shared among the different actors in geometrical variations management to achieve a coherent and complete tolerancing process leading to ensured product quality at moderate cost. Due to the manifold repercussions of these tolerancing activities on design, manufacturing, inspection and assembly, there is no doubt that an efficient processing of tolerancing information throughout and between companies is of strong importance.

Motivated by this, we propose the term tolerancing informatics. For the first part we refer to the definition of tolerancing as the set of activities which manage the tolerances during the product development [2], while the term informatics as coined by Karl Steinbuch [14] can be defined as automatic information processing. Thus, tolerancing informatics covers all attempts to achieve (semi-) automated information processing workflows to support the activities that manage tolerances throughout the product life cycle and, in a broader sense, also all activities that relate to geometrical variations management in general. In this context, depending on the available tolerancing information, interfaces, and computer-aided tools, different levels of automation can be achieved by these tolerancing informatics workflows. As a consequence, tolerancing informatics links all different activities in geometrical variations management and allows a continuous and seamless data and information transfer between them (see Figure 2).

Considering the increasing digitalization in design and manufacturing, tolerancing informatics can be expected to have a similar importance for research and industry as tolerance specification or tolerance analysis, particularly in the context of geometrical variations management 4.0 as a comprehensive digital process supported by various computer and software tools aiming at controlling and minimizing the effects of geometrical deviations [1].

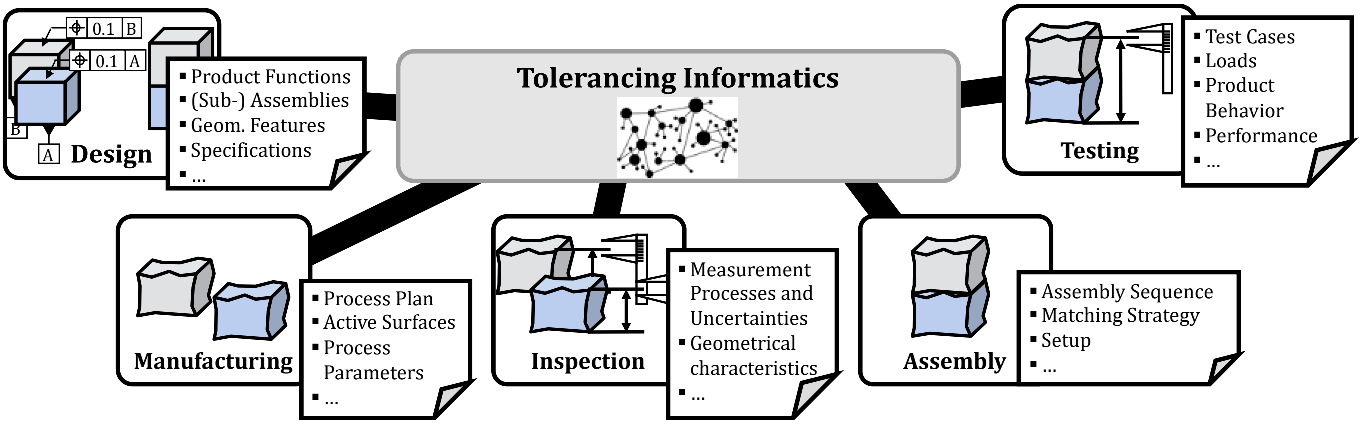

Figure 2. Tolerancing informatics as a seamless link between all activities in geometrical variations management.

3.3. Enablers of Tolerancing Informatics

The core enabling technologies can be subdivided in technologies that enable an automatic processing of specification-related tolerancing information and of verification-related tolerancing information (see Figure 3). Regarding the first aspect, fostered by the increasing digitalization of manufacturing, recent standardization efforts allowing the unambiguous specification of tolerances in three-dimensional part views of technical drawings and thus also in three-dimensional part models via model-based definition (MBD) are an important enabler of tolerancing informatics workflows, since they form the basis for creating unambiguous and semantic (three-dimensional) tolerance specification information in engineering design. Moreover, standardization efforts (ISO and ANSI) and their implementation by Computer-Aided Design (CAD) system vendors concerning the exchange of product data, such as STEP AP 242, are important for the automatic processing and exchange of tolerancing information by and between different computer-aided design, computer-aided manufacturing, and computer-aided inspection tools.

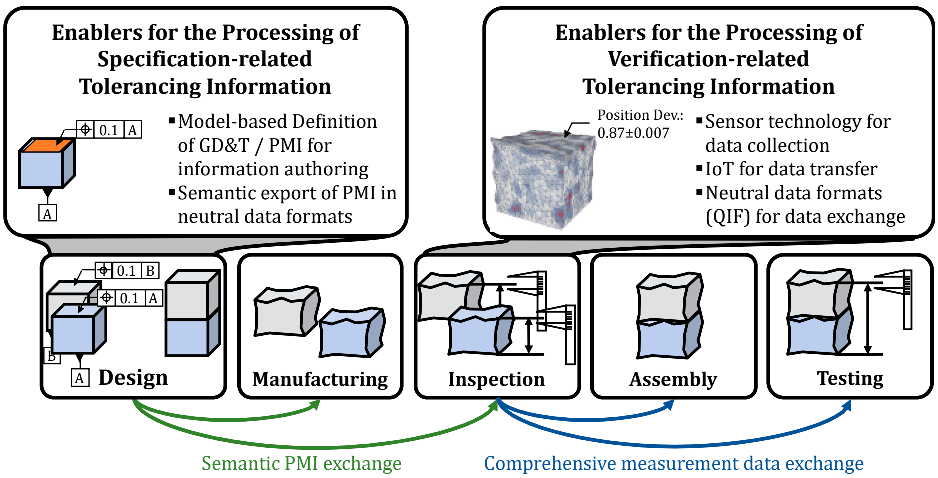

Figure 3. Main enablers for automatic tolerancing information processing. GD&T: Geometric Dimensioning and Tolerancing; PMI: Product Manufacturing Information; QIF: Quality Information Framework.

Considering the automatic processing of verification-related tolerancing information, the adoption of Quality Information Framework (QIF) for the exchange of tolerancing and metrology information ensures digital continuity between specification and verification data. Moreover, modern sensor technologies but also Industry 4.0 fostered by the advent of the internet of things (IoT) are important enablers in the form of a technology push towards tolerancing informatics workflows, since these technologies allow the quick sensing of geometrical part and assembly characteristics and their transfer to data storage and processing units in smart manufacturing systems.

Beside this, sophisticated tolerance and variation simulation tools in the form of digital twins for geometrical variations management, such as those presented in [15] based on fundamental concepts of standards for the geometrical product specification and verification or as proposed in [16], are important enablers for tolerancing informatics workflows. This is because they allow the modelling and processing of instantiated part variation information in real-time and thus enable the realization of smart assembly and advanced matching strategies [17].

3.4. Tolerancing Informatics Workflows

The automatic processing of tolerancing information is useful in many different geometrical variation management workflows. For example, the automatic transfer of specification-related tolerancing information from computer-aided design tools to computer-aided manufacturing and inspection tools (Figure 4, middle, green arrows) will eliminate the need for manual processing of tolerance annotations on technical drawings to the input devices of manufacturing and coordinate measuring machines as a part of process or inspection planning activities [1].

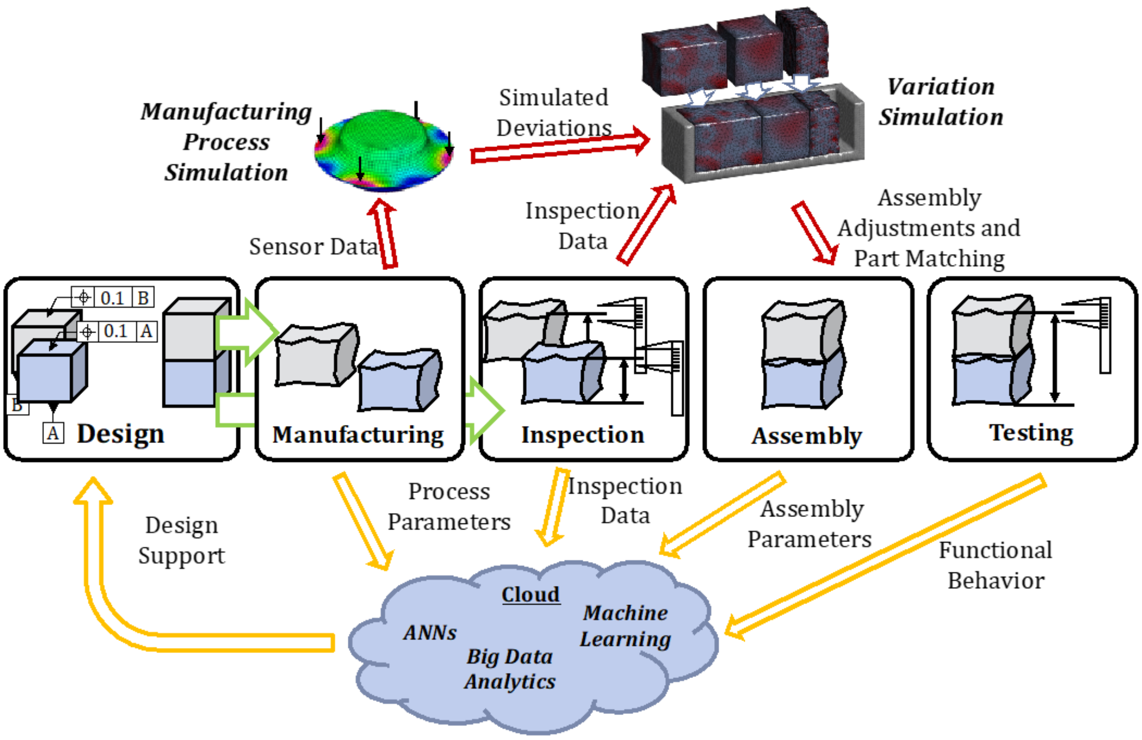

Figure 4. Exemplary tolerancing informatics workflows. ANNs: Artificial Neural Networks.

Moreover, the automatic processing of verification-related tolerancing information obtained during part inspection at the assembly stage will allow for more sophisticated matching strategies (Figure 4, top, red arrows). Combined with the automatic processing of specification-related tolerancing information, this will allow a continuous digital thread in geometrical variations management. Additionally, the feedback-to-design loops will benefit from automatic tolerancing information processing. This is because manufacturing variation databases can be automatically filled with process capability information. These databases can then be used for data driven tolerance specification during design by automatic knowledge acquisition using machine learning and other data analysis techniques (Figure 4, bottom, orange arrows).

In the following, these three exemplary workflows are described in more detail.

3.4.1. Automatic Transfer of Specification-Related Tolerancing Information

It is widely acknowledged, that, due to the strong repercussions of tolerancing decisions on manufacturing, inspection, and assembly cost as well as on the product function, tolerance specification (deriving adequate tolerancing schemes) and tolerance allocation (allocating adequate values to these tolerances) are highly responsible design tasks. Though these tasks are typically performed in late design stages based on expert knowledge, current research efforts focus on the early and automatic generation of functional specifications from design knowledge [18] and on the knowledge-based tolerance allocation [19].

However, nowadays in many companies, the information transfer regarding these tolerance specifications from design to manufacturing and inspection is highly dependent on error-prone manual interventions. This is because these tolerance specifications from design have to be manually entered in software tools for the computer-aided process planning or computer-aided inspection. In contrast to this manual process, tolerancing informatics workflows allow the automatic transfer of specification-related tolerancing information to all downstream activities. In order to achieve this, several research works have been proposed, which focus on the interoperability between product definition and measurement planning [20] as well as on selecting and developing adequate exchange formats between computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided inspection (CAI) tools [21,22]. Moreover, approaches for the mapping of these tolerance specifications from higher-level CAD exchange formats, such as STEP (Standard for the Exchange of Product model data), to lower-level geometry exchange formats, such as STL (Stereolithography), have been proposed [23] as well as methods to include such STL files in modern tolerancing informatics workflows [24].

The automatically transferred specification-related tolerancing information can be modelled using different representation schemes [11] and used for the automatic quality assurance of parts [25]. Moreover, recent advances regarding the management of obtained measurement data [26] help to further process the obtained verification-related tolerancing information to assembly and testing, where this information can be used for applying assembly adjustments and advanced matching strategies.

3.4.2. Assembly Adjustments and Advanced Matching Strategies

Industry 4.0 and the internet of things as well as the increasing digitalization in manufacturing lead to an increased gathering of sensor data from manufacturing machines and processes. In order to use this data for controlling and managing geometrical variations, it can be used as input data in manufacturing process simulations to predict the systematic part variations, which can in turn be further processed. Moreover, as a result of inspection activities, it is known if the parts conform to the specified tolerances and information about the actual part geometries in the form of measurement data are available (also considering uncertainties).

These results from manufacturing process simulations or measurement data can be processed in tolerance analysis and variation simulation models to predict the behavior of the assembly. In this context, depending on the required simulation model fidelity, measurement point reduction techniques allow for simpler models to be equipped with meaningful measurement data [27], while advanced tolerance analysis and variation simulation methods based on the concept of "skin model shapes" [28] allow for a realistic prediction of the assembly behavior considering the complete measurement point set.

The efficient processing of the verification-related tolerancing information enables the implementation of advanced matching strategies [29], i.e., identifying suitable assembly partners that reduce geometrical variation. Moreover, such data processing allows for building a digital twin for geometrical variations management [15] and geometry assurance [16]. Beside the aforementioned matching strategies, such digital twins allow for the individualizing of locator adjustments [30] or the selective assembly of sheet metals [31].

However, the implementation of a digital twin for geometry assurance still entails some challenges in industry [17].

3.4.3. Feedback to Design for Knowledge-Based and Data-Driven Tolerance Specification

The automatic processing of tolerancing information as well as the data and information gathering and storage in digital manufacturing clouds enables the application of data analytics approaches to assess the complex relationships between design tolerances, manufacturing process parameters, inspection routines, assembly adjustments, and testing procedures. In particular, such meta-modelling and data analytics methods allow for the derivation of suitable manufacturing process parameter windows that ensure the required product quality.

However, as it has been highlighted, the proper choice of tolerance specifications and values during design is of utmost importance for efficient manufacturing and reliable product function during use. In this context, verification-related tolerancing information in the form of inspection data can be used to support the robust design in early design stages [32]. Moreover, data about the relationship of part tolerance specifications and manufacturing difficulty can be used by advanced data-mining methods (see e.g., [33]) to derive tolerance-cost curves (eventually considering process capability effects as in [34]), which in turn enable a cost-efficient tolerance design using tolerance-cost optimization [35].

3.5. Application and Benefits of Tolerancing Informatics Workflows

Isolated parts of the vision towards a continuous digital thread in geometrical variations management by tolerancing informatics workflows have already been the subject of investigation in different research works. In this regard, a digital framework for the real-time quality control of welded components has been proposed in [36]. Furthermore, the paradigm of process-oriented tolerancing as a means of adjusting the part tolerances in an assembly in accordance with the capability of their manufacturing processes will hugely benefit from automatic tolerancing information processing [37]. This is supported by methods to the automatic mapping of tolerancing and product manufacturing information from STEP to tessellated product geometry models [23]. Moreover, advanced matching strategies in assembly have been reported in [29], which make use of sensor data and their processing in digital twins.

The main reported benefits from these applications are reduced development lead times and cost-savings in manufacturing, inspection as well as testing of mechanical assemblies and the possibility for individualized production.

4. Discussion

As it can be seen from the aforementioned tolerancing informatics workflows, the automatic processing of tolerancing information along the different stages of the product origination process will change and improve current best practices and workflows for the management of geometrical part variations throughout the product lifecycle. Though important research efforts in this direction have been reported recently, there is still a lack of a complete and continuous digital thread between all different geometrical variation management activities.

In this context, for example data-driven support for the functional tolerance specification (i.e., automatic derivation of tolerance specifications for given product functions), the availability of standardized interfaces for specification- and verification-related tolerancing information between different computer-aided design and tolerancing tools and the possibility to build and operate holistic digital twins in geometrical variations management are open issues and require future research. In this regard, multiple scenarios can be foreseen if tolerancing informatics research will lead to an extensive computer-aided tolerancing (informatics) tool or if various smaller applications will contribute to establishing different tolerancing informatics workflows. New insights from geometrical variations management that have emerged from new manufacturing processes, such as additive manufacturing and simulation-driven product design, will also have an impact on the future evolution of tolerancing informatics.

However, as this paper presents the first comprehensive overview of tolerancing informatics, future studies in this domain should focus on the implementation of specific tolerancing informatics workflows and provide detailed insights on how to achieve the reported benefits in academic and industrial environments.

5. Summary and Conclusions

Due to their important effects on product quality and cost, the management of geometrical variations is both a complex and responsible task which covers various different activities. As a result, geometrical variations management strongly relies on the gathering, processing, sharing and dissemination of tolerancing information and knowledge. However, up until now, this has required many manual efforts and interventions. New means for automatic information processing are required in future geometrical variations management to make full use of novel digitalization paradigms, such as industry 4.0 and digital twins. To achieve this, the paper proposed the term tolerancing informatics, which summarizes all attempts to achieve automated information processing workflows to support the set of activities that manage tolerances throughout the product life-cycle and that relate to geometrical variations management. Beside this, new concepts and means for automatic information processing, novel information sharing workflows as well as the integration of tools for next generation digital geometrical variations management have been highlighted.

Though automatic tolerancing information processing workflows have already been partly reported in recent scientific works, future research is required to achieve a fully continuous digital thread in geometrical variations management. However, considering the increasing digitalization in design and manufacturing, tolerancing informatics can be expected to have similar importance for industry and academia as tolerance analysis and tolerance specification.

Author Contributions: Conceptualization, B.S.; methodology, B.S. and N.A.; validation, B.S. and N.A.; formal analysis, B.S. and N.A.; investigation, B.S.; writing—original draft preparation, B.S.; writing—review and editing, B.S. and N.A.; visualization, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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