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Review

Process-Oriented Tolerance and Variation Management: Review and Classification

Philipp Litzenburger [1,†], Stefan Goetz [2,*], Lennard Margies [3], Christoph Bode [2,†], Rainer Müller [1,3] and Sandro Wartzack [2]

1 Chair of Assembly Systems, Department of Systems Engineering, Saarland University, 66121 Saarbrücken, Germany; philipp.litzenburger@mst.uni-saarland.de (P.L.)
2 Engineering Design, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
3 Assembly Systems, Center for Mechatronics and Automation Technology gGmbH, 66121 Saarbrücken, Germany
* Correspondence: goetz@mfk.fau.de
† These authors contributed equally to this work.

Featured Application: This paper is intended to provide future researchers and users with an overview of concepts and modeling approaches for process-oriented tolerance and variation management. This should facilitate the identification and development of appropriate concepts.

Abstract: In the context of tolerance management, the consideration of manufacturing and assembly processes is becoming increasingly important. The main drivers for this are, above all, short development times and high-quality requirements, leading to tight tolerances. To overcome the resulting challenges, many publications address the process-oriented tolerance management. However, since multiple terms and definitions for describing activities that link tolerance management with the production process exist, it is hard to obtain a comprehensive overview on the topic. Therefore, this paper presents a review of existing approaches. The aim is to identify similarities and differences of existing approaches and present them with the help of a classification. For this purpose, among others, work from the areas of process-oriented tolerance management, stream of variation, state space modeling, and variation propagation in multistation manufacturing and assembly systems is considered. Based on the definition of the summarizing term "process-oriented tolerance and variation management", a classification of this thematic area will be introduced.

Keywords: process-oriented tolerancing; stream of variation; state space modeling; process-oriented tolerance and variation management

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1. Introduction

The process-oriented perspective in tolerance management represents an extension of the classical function-oriented approach to tolerance management [1]. In general, the inherent imperfections of the production processes necessitate the use of product tolerances to ensure the interchangeability of parts and components. The discrepancies that accrue throughout the production process can be classified as either manufacturing or assembly errors. In the past, tolerance analysis and synthesis have largely concentrated on product variables, with the objective of guaranteeing part and component interchangeability [2]. This form of tolerance management typically considers only the function of the final product at the end of the production process. Consequently, it can be characterized as function- or product-oriented tolerance management/tolerancing [1]. In this approach, the specification of the tolerance is often based on experience, tables, or standards [3]. Process information is indirectly and implicitly incorporated into this product-oriented tolerancing [2]. Despite this indirect consideration of process information, the technical possibilities and limitations of production are often ignored [3]. However, the increasing demands on manufacturing, assembly, and supplier management are elevating the importance of including process variables as a significant consideration. This is particularly the case with regard to the interchangeability of processes, such as when different suppliers manufacture the same component using different processes [2]. The process information is also essential for determining the optimal tolerances [1]. Variations in process parameters have a significant impact on product deviations, not only in manufacturing but also in assembly processes [1]. Therefore, it is essential to give greater consideration to process parameters and information [2]. This includes process parameters and information from the manufacturing, assembly, and measurement process, such as locator dimensions and variations [2], fixture layouts [4], but also joining and spot welding sequences [5,6], spindle thermal variations and cutting tool wear variations [7], measurement uncertainties [1], or interactions along the process chain [2]. This results in the aforementioned process-oriented tolerance management, in which process information from manufacturing, measurement, and assembly is taken into account in order to determine optimal tolerances (Figure 1) [1].

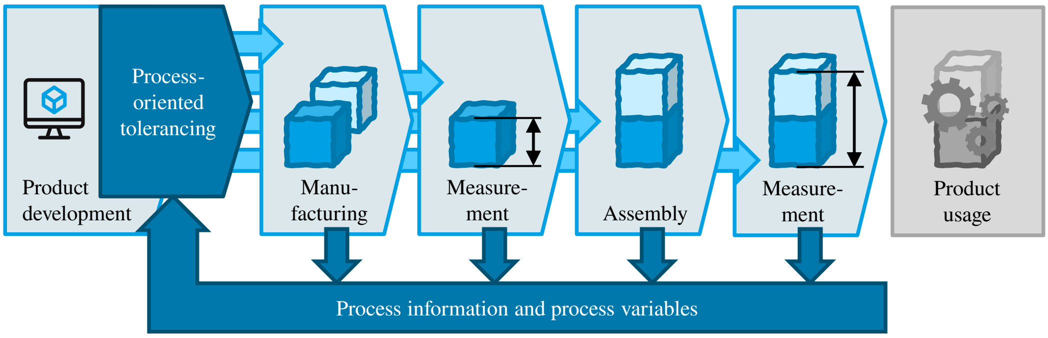

Figure 1. Process-oriented tolerancing based on [1,3].

Therefore, the literature provides numerous concepts regarding process-oriented tolerancing [8]. The most prominent approaches in this field are, of course, those that describe themselves as process-oriented tolerancing or process-oriented tolerance management. Examples include Ding et al. [2], Abellán-Nebot et al. [9], Heling et al. [10], and Müller et al. [11]. However, there are significant differences in their specific implementations and scopes.

Ding et al. and Abellán-Nebot et al. both use the stream of variation (SoV) with a state space model to represent the variation propagation as the basis for their process-oriented tolerancing [2,9,12]. Ding et al. specifically focus on multistage assembly systems, modeling not only variation propagation but also the tolerance–variation relation and process degradation. In the context of tolerance synthesis, this approach is intended to optimally allocate tolerances to the fixture in the assembly process [2]. Abellán-Nebot et al. analyze multistage manufacturing processes using an extended SoV approach. The approach includes critical process variables and cost functions [9,12]. Heling et al. adopt a comprehensive perspective and attempt to predict deviations based on process variables while optimizing tolerance allocation. Surrogate models, vector models, and skin-model shapes are used, among other things, for this purpose [10]. In contrast, the approach of Müller et al. is more reactive and focuses on the use of user-oriented methods such as the key characteristics flowdown and tolerance chains. This is intended to ensure the practical application of the approaches in the planning and optimization of assembly systems [11,13].

In addition to these approaches, which describe themselves directly as process-oriented, there are other methods that can also be used for process-oriented tolerance management. For instance, the variation analysis and the modeling of variation propagation are crucial components of tolerancing, especially in a process-oriented approach [14–16]. Different types of modeling exist for this purpose. For example, the SoV approach with the state space model is widely used, as demonstrated in the aforementioned publications of Ding et al. [2] and Abellán-Nebot et al. [9]. Another option is to model variation propagation using dual quaternions, as shown by Yacob et al. [4,17–19].

These examples demonstrate the variety of terms in this context, indicating a lack of overview and structure in the extended definition of process-oriented tolerancing. Therefore, the authors define "process-oriented tolerance and variation management" (PTVM) to outline this subject. Additionally, this paper proposes a classification for existing methods and approaches in the context of PTVM.

This paper is subdivided as follows: After the introduction in Section 1, the method of the literature research follows, and the classification is explained in Section 2. Section 3 provides the classification results and the main approaches. Based on that, a discussion of the classification follows in Section 4. The paper concludes with a summary and an outlook in Section 5.

2. Method

2.1. Definition of PTVM

As mentioned in the introduction, there are numerous terms related to tolerance management, taking into account production processes. However, some of these terms are used inconsistently, leading to an unclear definition of the subject. In order to address this lack of clarity, first, a term must be chosen and defined that describes the subject area to be delimited as comprehensively as possible. Existing terms are not suitable, since they usually describe only a subarea of the underlying topic or are defined differently by different authors. For example the term "process-oriented tolerancing" is used by Ding et al. [2], Abellán-Nebot et al. [9], Heling et al. [10], and Müller et al. [11] with different definitions.

Therefore, the term PTVM is introduced at this point. It is defined as "tolerancing approaches or methods considering process variables or reducing variations by modifying the process or its parameters". Therefore, it includes single and multistage processes and is not limited to prediction alone but also includes the concrete implementation of actions to reduce deviations. The main goal is to better delineate the subject area in order to simplify research and to provide a basis for discussion based on a clearly defined term.

2.2. Literature Research Method

The literature research followed the PRISMA statement, specifically the PRISMA flow diagram [20]. The identification of the relevant works in the subject area was carried out on the basis of three approaches: A syntax-based review with the search engine and database "google scholar" [21] and the scientific social network "researchgate.net" [22], a research based on similarities in publications based on the tool "connected papers" [23] and a source review of available papers. A preliminary stage in the literature research involved the identification of significant keywords and publications through a detailed examination of the existing literature, including an analysis of the literature's bibliographies, thus establishing an initial set of keywords, such as "process-oriented", "process-oriented tolerancing", "process-oriented tolerance management", "variation propagation", "state space modeling" or "stream of variation". The review based on "google scholar" and "researchgate.net" was carried out with relevant keywords mentioned before. Using connected papers, it is necessary to specify a source publication. On this basis, relevant papers are proposed by comparing the citations and references. Ding et al. [2] was used as the main source publication. It was selected because it was the first one on process-oriented tolerancing and is frequently cited, providing a good illustration of the subject area. The research was completed on 13 August 2024. With all three procedures, a total of 199 publications were identified.

Preselections were made based on the title and abstract due to the large number of publications. The preselection yielded 146 publications, which were further analyzed for their suitability to the subject area and subsequent classification. After this further examination, a total of 124 publications were included in the review and the classification. The most significant and determinative selection criterion was that the approach incorporates process parameters and/or modifies or optimizes them. The selection process was conducted manually by the two main authors[†]. The detailed procedure is shown in Figure 2.

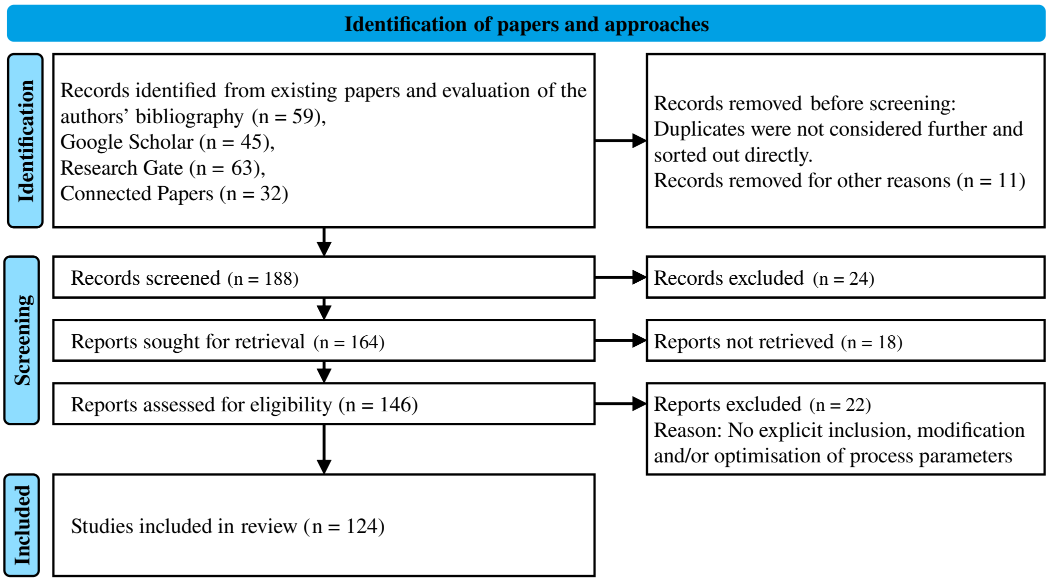

Figure 2. PRISMA flow diagram.

2.3. Classification Approach

The objective of this paper is to enhance the accessibility of the field of PTVM and to provide a structured framework for its associated methods, models, and approaches. This should assist users of such models, as well as prospective researchers, in gaining an overview of the subject area and in identifying comparable or existing solutions more expeditiously for a particular application. In light of the aforementioned introduction, which highlighted the considerable diversity in the terminology and scope of the field, such an overview is particularly beneficial. In view of the extensive literature on this topic, it is necessary to further subdivide and classify the results of this review in order to improve clarity and to assist the reader, for example, in the selection of existing approaches. For this reason, the relevant researched publications are classified. A variety of distinguishing criteria may be employed for this purpose. In this context, it could be useful to distinguish between whether manufacturing or assembly processes are being considered, the methods and models applied, and the scope of consideration—i.e., whether a specific single process is examined in great detail or whether a process chain with its interactions is considered. In accordance with the authors'† view, the most significant similarities and differences in the application of methods and models can be identified in the consideration of single processes and process chains. Thus, this classification is employed in this publication.

The primary difference in the application of individual methods and models is often whether specific parameters within a process and their effects on the process outcome are modeled, or whether the focus is on the interactions and variation propagation within a process chain. In addition, the user typically has a specific use case they wish to analyze. This may be a single process or multiple processes along a process chain. If the user wants to analyze and model specific process parameters of a single process in detail, it is helpful to have an overview of possible solutions that also focus on a single process in detail; interactions with preceding or subsequent processes are initially irrelevant. With this overview, they are now able to find existing solutions to their problem or possibly adopt similar solutions. If, for example, the classification was based on the models used, a use-case-specific overview of existing solutions would not be possible. In this case, the user would either have to examine all modeling approaches for a comparable use case or already have a precise understanding of which modeling approach is most appropriate. A purely binary distinction between manufacturing and assembly would obscure the overview of similar considerations, such as variation propagation through the fixture layouts and locator variations, which affect both assembly and manufacturing. In addition to approaches that focus on single processes or process chains, there are also approaches that are explicitly suitable for considering both process chains and single processes, as well as approaches that focus on a higher-level perspective and consider PTVM more from an organizational point of view.

Therefore, the classification consists of four classes: analysis of process chains, analysis of single processes, approaches for analyzing process chains and single processes, and overarching process-oriented tolerance management approaches.

The class "analysis of process chains" always includes approaches that consider variations, tolerances, or influences along a complete process chain. A process chain refers to the sequence of multiple stations, between which a workpiece has to be handled, or to multiple self-contained processes, such as a milling process followed by a drilling process. The focus is on examining the relationships between the processes, while the modeling of the single processes is of secondary importance.

The "analysis of single processes" class summarizes approaches that examine a single process in detail to make statements about variations, for example. The processes can also be subdivided into sub-processes. This class also includes the modeling of discrete stations, where the variations caused by loading into the fixture and subsequent processing, or the welding spot sequence, are modeled. In certain instances, individual processes are analyzed to determine variation values for later consideration in the process chain. This class also includes the use case of a hollow box and two circular profiles, frequently used by Corrado et al. [24–28], and Polini et al. [29,30], among others, as no explicit process chain or interactions due to a sequence of different stations are considered.

The class "approaches for analyzing process chains and single processes" includes methods that are explicitly suitable for analyzing both individual processes and process chains. However, this must be clearly stated and emphasized in the validation. In most cases, the validation focuses on a specific use case, such as a single process or a process chain. Although a universal application is hypothetically possible, the authors have not directly considered it, and it is therefore assigned to one of the other classes.

"Overarching process-oriented tolerance management approaches" are approaches that focus on a holistic (process-oriented) tolerance management process without focusing directly on process chains or single processes. However, process parameters are still considered. The aim is usually to optimize tolerances and/or costs throughout the product life cycle. The approaches describe a procedure at a higher level, rather than specific modeling of processes, sub-processes, or process chains.

Figure 3 displays the individual classes. Section 3 provides a more detailed account of the number of publications assigned to each class and their main approaches.

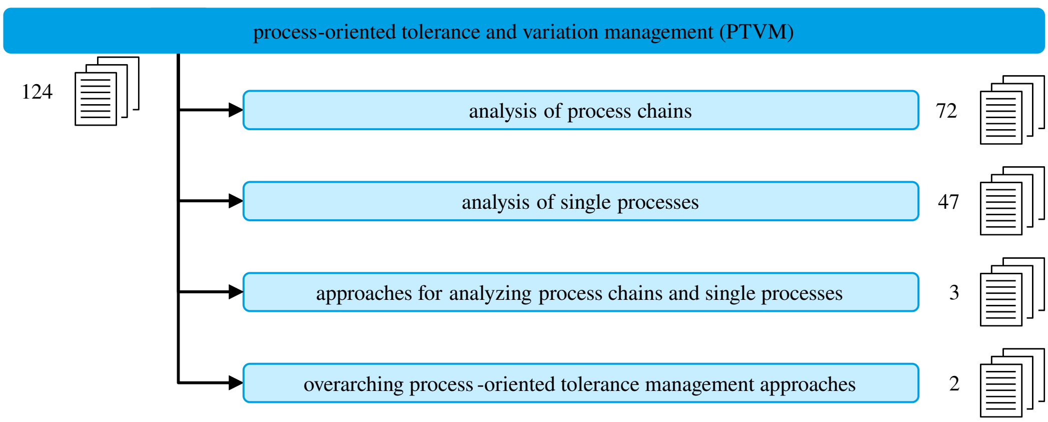

Figure 3. Classification of PTVM.

3. Classification Results and Main Approaches

3.1. Analysis of Process Chains

A total of 72 publications can be assigned to the "analysis of process chains" class. The majority of these publications describe the modeling of variation propagation in the process chain. This can be achieved in various ways. Abellán-Nebot et al. identify two primary modeling approaches for variation propagation in manufacturing—the previously mentioned SoV and the Model of Manufacture Part. The SoV method is particularly suited for process-oriented tolerancing, among other applications. The Model of Manufacture Part, on the other hand, is preferable for product-oriented activities [31,32]. Abellán-Nebot et al. compared the two approaches in a publication [32], to which reference is made here for a detailed differentiation. The significance of the SoV approach and the state space model for this class is also demonstrated by the fact that 52 out of 72 publications employ this approach or this form of modeling.

The concept of SoV was introduced by Hu et al. [33] about 25 years ago [14]. The original goal of the concept was the diagnosis and prediction of dimensional variations in a multistage automotive body assembly [33]. The most common form of mathematical modeling is the state space model, which was first used in the SoV context by Jin and Shi [34] in 1999. The state space model was adopted from control theory. It describes the mathematical relationship between the sources of variation and the product deviations in multistage processes [12]. The kinematic relationships of the production are represented here by transformations. The matrix entries are constants defined by the product and process design. This modeling allows the simultaneous consideration of multistage production systems and different process routes [35,36]. The following is the basic mathematical representation of the state space model by Huang [35]:

$$\boldsymbol{x}_k^{(i)} = \boldsymbol{A}_{k-1}^{(i)} \boldsymbol{x}_{k-1}^{(i)} + \boldsymbol{B}_k^{(i)} \boldsymbol{u}_k^{(i)} + \boldsymbol{\xi}_k^{(i)}, \tag{1}$$

$$\boldsymbol{y}_k^{(i)} = \boldsymbol{C}_k^{(i)} \boldsymbol{x}_k^{(i)} + \boldsymbol{\eta}_k^{(i)}, \tag{2}$$

$\{k\} \subset \{1, \ldots, N\}$ and $\{i\} \subset \{1, \ldots, R\}$ according to [35];
$\boldsymbol{x}_k^{(i)}$—deviation of a part characteristic;
$\boldsymbol{y}_k^{(i)}$—deviation of a quality characteristic of the product;
$\boldsymbol{u}_k^{(i)}$—deviations induced by the process;
$\boldsymbol{A}_{k-1}^{(i)}$—state transition matrix;
$\boldsymbol{B}_k^{(i)}$—input matrix;
$\boldsymbol{C}_k^{(i)}$—observation matrix;
$\boldsymbol{\xi}_k^{(i)}$, $\boldsymbol{\eta}_k^{(i)}$—error terms that include, for example, other non-modeled errors or sensor noise;
i—process route;
k— process stage [35,36].

The SoV approach, as well as the state space modeling itself, is first detailed and complemented by a series of publications around Ding et al. [2,37–41]. Furthermore, the approach is extended to multistage manufacturing systems by Huang et al. [42] and Djurdjanovic et al. [43]. The approach is improved by Zhou et al. [44] in the context of introducing the differential motion vector. This has its origin in robotics and represents the geometric deviations [12]. Extensions by Loose et al. [45], Abellán-Nebot et al. [7,12,31,46], and Huang et al. [47] consider additional fixture layouts and manufacturing errors [19]. A further addition to the approach is made by Wang's et al. [48] consideration of components with a variable stiffness structure.

In a series of publications [4,17–19], Yacob et al. present an additional approach to modeling the variation propagation in a multistage manufacturing process utilizing dual quaternions. The approach considers deviations in fixtures in various layouts [4,19] and manufacturing deviations [17,18]. It is associated with the SoV, among others, and also uses the skin model shapes [19].

Furthermore, Wärmefjord et al. describe a method for simulating variation in [49], which builds upon a model for evaluating error propagation developed by Carlson et al. [50].

In addition, other models have been employed, including Markov models, surrogate models, and skin-model shapes. Notable applications of Markov models include the work of Du et al. [51] in the modeling and analysis of multi-product, multistage manufacturing systems and that of Huang et al. [52] in the modeling of variations in multistage steel production. In their study, Hofmann et al. [53] employ skin-model shapes to model the machining processes involved in multistage single-part production. Heling et al. [54] employ surrogate models to ascertain the impact of dispersing manufacturing process parameters.

An overview of these and all other publications and approaches to analyzing process chains can be found in Table A1 in Appendix A.

3.2. Analysis of Single Processes

The "analysis of single processes" category is the second largest, with 47 publications. The approaches and models used in this category are more diverse than those in the previous category. Therefore, only a selection of possible approaches for analyzing single processes is presented below. All assigned publications and approaches can be found in Table A1 in Appendix A.

The approaches developed by Polini et al. and Corrado et al. for tolerance analysis or variation modeling are largely assigned to the single process class. This is particularly applicable to the use case of a hollow box and a couple of circular profiles [24–30], as it theoretically models a general, abstract assembly process without considering further interactions between different processes in a process chain. Further considerations focus on glue modeling [55], deviations in drilling [56], and milling [56,57] or on the manufacture of lightweight products [58,59] and thus correspond to a consideration of single processes. Generally, the approaches by Polini et al. and Corrado et al. consider manufacturing signatures [24–30] and operating conditions [24,25,27,28,30]. Various procedures including Jacobian, torsor, variational, and vector loop are utilized and compared with each other [25,26]. Moreover, they develop and employ a new variational model [28,29].

The approaches and methods of Wärmefjord and Söderberg for variation simulation are predominantly categorized as "analysis of single processes". The majority of the publications concentrate on the particular modeling and simulation of specific influences and properties inherent to a given process. Examples of this include the development of a method for transforming the variation in the test data into variations in the contacts between the workpiece and the locators [49], the use of critical material and process parameters and the resulting geometric deviations in a meta-model [60], and the development of a method for analyzing the variation in surface-to-surface contact of a cutting tool [61]. In particular, the working group employs a detailed analysis and simulation of welding processes. Furthermore, the class "analysis of single processes" is also the subject of their detailed consideration. Various factors are used to simulate variations or optimize the joining and spot welding sequence. These include heating and cooling processes together with the geometric tolerances of the components [62], the spot welding sequence [5] including the springback calculation [63], and the joining sequences [6,64], joining points [64], and joining forces [64]. Tools like the Method of Influence Coefficients (MIC) [63] are utilized for this purpose.

The MIC is also employed in other publications, for example, by Khodaygan et al. [65] to assess the assembly configuration when analyzing flexible sheet metal structures or by Mei et al. [66] in the variation analysis for compliant aerostructure assembly.

Mei et al.'s "rigid-compliant hybrid variation analysis method" also falls under this category. It is used to analyze ladder structures, primarily for the aircraft structure assembly. The analysis is centered on variations resulting from rigid body locating errors and part geometric errors. They are modeled using rigid-body kinematics and mechanistic methods, and subsequently integrated into a rigid-compliant hybrid variation model. Due to the low production volume in the aircraft industry and the often-unknown probability distribution, Mei et al. propose a novel variation analysis method. A Monte Carlo interval approach is used for this [67].

As previously outlined, the approach adopted by Müller's research group is primarily oriented towards practical applications and a systematic methodology. In this context, particular emphasis is placed on the utilization of key characteristics, key characteristic flowdown, and tolerance chains. The present study is exclusively concerned with assembly processes or corresponding sub-processes. The approach is more reactive, so usually, an existing assembly system is analyzed and, if necessary, optimized through the use of other equipment or measurement technology. The majority of publications focus on a specific process, which is why they are classified within this category. For example, processes such as aircraft fuselage section assembly [68], an aircraft riveting process with a semi-automated, collaborative human–robot system [11], and fully automated robot-supported assembly processes in engine production [69,70] are considered.

It has been demonstrated on numerous occasions that certain modeling approaches can be employed for both individual processes and process chains. The specific extension, the use in combination with other methods and models, and the influences, properties, and boundary conditions of the use case taken into account are the decisive factors for the application and classification. Therefore, the SoV approach can also be used to a certain extent in this context. This is shown, for example, by Huang et al. with a variation model for the assembly of rigid bodies in a single station [71], Zhang et al. with the variation analysis for the assembly of compliant composite parts [72], or Abellán-Nebot et al. with an extension to include variations from workholding devices [46].

Other examples, which are also used above in the "analysis of process chains", are the skin-model shapes and surrogate models. In their study, Junnan et al. [73] employ skin-model shapes to address the issue of deformation and manufacturing errors in the tolerance analysis of an assembly process. Similarly, Moro et al. [74] utilize this approach in their tolerance analysis of an assembly of composite parts. As an example of the use of surrogate models, Franz et al. [75] employ them for the optimization of tolerances in locally reinforced composite structures.

3.3. Approaches for Analyzing Process Chains and Single Processes

This class is assigned a total of three publications. Mende's "characteristic formation and interaction analysis (MEWA)" [36] presents a method that can be used for both single processes and process chains. The concept is based on the DMAIC cycle (Define, Measure, Analyze, Improve, Control). The methods for the process-oriented tolerance management in an assembly are to be applied from four perspectives: characteristics relationships, material flow relationships, causal analysis, and statistical analysis. These four perspectives are used to gain a comprehensive understanding of the tolerance problem. An important component of the causal analysis is the newly developed characteristic formation trees. These can be set up both functionally and in a flow-oriented way. This allows the perspective of the characteristic and material flow relationships to be mapped and documented. With the flow-oriented characteristic formation tree, the interactions in the material flow of an assembly can be represented. However, single stations and single processes can also be considered, as shown in the validation scenario "sand core". The concept was developed as part of her dissertation in Müller's research group. It can therefore be assigned to the above-mentioned understanding of process-oriented tolerance management by Müller et al., which focuses primarily on a practical and user-oriented approach [36].

Another approach is the "interdisciplinary process-oriented tolerance management" presented by Heling et al. [10]. With this approach, it is possible to simulate single manufacturing processes in great detail. The knowledge gained from the single manufacturing processes is in turn used for a tolerance analysis of the key functional characteristics of the final product. This implies that single processes can be analyzed in great detail, but the information can also be used comprehensively [10]. This approach is part of Wartzack's research group, which, as previously stated, is engaged in the investigation of optimal tolerance allocation through the utilization of a process-oriented tolerance management approach. The impacts of the manufacturing process and operational factors are subjected to comprehensive examination. In order to achieve this, single processes, such as the extrusion process for metal gears and the injection molding process for plastic gears, are modeled and simulated. Furthermore, the deviations that occur throughout the entire process chain on the subsequent product are also taken into account [1].

3.4. Overarching Process-Oriented Tolerance Management Approaches

This class is assigned two publications. One of them is the framework of Schleich et al. [8] for process-oriented tolerance management. The framework aims to provide an integrated view of process-oriented tolerancing by incorporating information from all phases of product origination. To achieve this, a concept is presented that integrates process information into a skin-model-inspired framework for computer-aided tolerancing. This approach offers the advantage of considering both product-related tolerances and the scattering of process parameters simultaneously. This approach can help to minimize costs related to tolerance. It primarily considers the exchange of information across different phases of product origination and is assigned to this class due to its general and overarching nature [8].

Andolfatto et al. present a method that is intended to support the selection of assembly techniques and the allocation of tolerances in order to reduce product costs and maximize the conformity rate in connection ro the assembly plan [76]. As specific process parameters, such as the assembly technique used, or the assembly plan, are considered here, this approach is also part of PTVM. However, as the approach focuses more on the selection of assembly techniques, tolerance allocation, and the assembly plan, this approach is also considered to be a more general approach, as single processes and stations are not modeled in detail [76].

3.5. Summary of the Results

Figure 4 illustrates the results of the classification. In addition to the number of associated publications, this figure provides an overview of the principal approaches, models, and methods employed in the analysis of process chains and single processes, together with the number of associated publications. This emphasizes the popularity of individual models, methods, and research group approaches, such as those by Polini and Corrado or Wärmefjord and Söderberg. Furthermore, the significance of the SoV and the state space model is evident in this context. It should be noted that the aforementioned labels (e.g., SoV and state space model) are used to group together individual publications that represent either a specific extension or further development of the approach or model in question. These extensions or further developments typically relate to a particular application case. While the general methods and models, such as the SoV and the state space model, or the variation simulation approaches of Wärmefjord and Söderberg, can be applied to both process chains and single processes, the classification always considers the specific content and application case of each publication. These are then usually clearly assigned to the appropriate class, e.g., “analysis of process chains”. As previously stated, this methodology is also beneficial for the user. In general, the user considers a specific use case, such as a single welding process, which they wish to analyze and model accordingly. It is beneficial for them to have an overview of potential modeling approaches for single processes in order to either identify an existing approach that is applicable to their use case or, at least, identify modeling approaches for similar use cases that they can adopt. This allows them to avoid studying approaches that only address process chains or higher-level and more organizational considerations, for example.

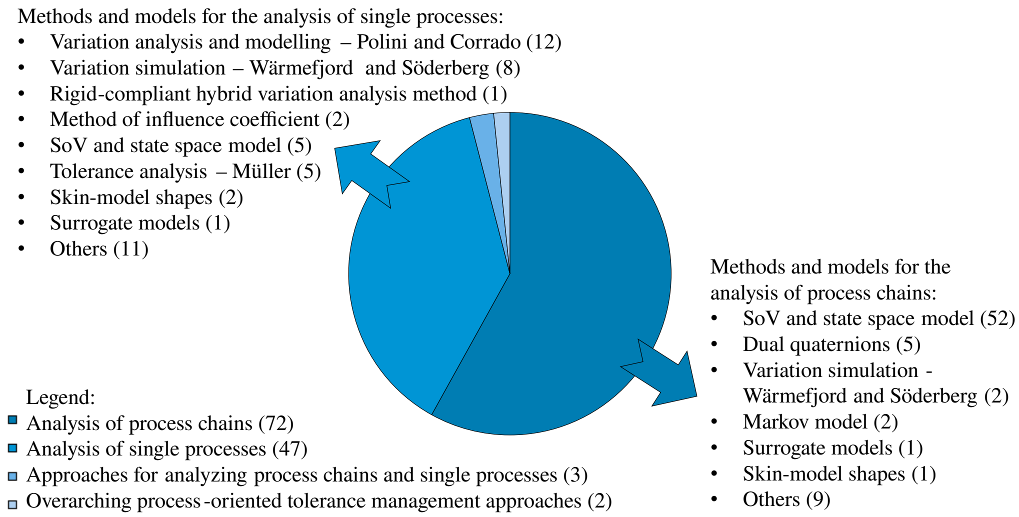

Figure 4. Summary of the classification results with an overview of the most popular methods, models, and approaches.

4. Discussion

This publication presents an initial effort to clearly define and categorize PTVM, offering an introductory definition of the term. This fact leads to some limitations in the classification.

The approaches and publications analyzed lacked a clear definition of the subject area, resulting in ambiguous delimitation and the use of identical terms for different approaches, as previously mentioned in the introduction. Therefore, distinguishing between existing approaches and categorizing them into individual classes is challenging. Furthermore, the selection of classes is also a first attempt to structure the field more clearly. In addition to the presented classification, other approaches are also possible. For instance, publications could be classified based on the concepts and models used. This paper also attempted such a classification. Nevertheless, the resulting concrete and fine-grained categorization would be of limited value in the context of this paper, given the significant differences in the level of detail and focus of the various papers under consideration.

Furthermore, distinguishing between publications that can be assigned to PTVM and those that no longer belong to this subject area is not always clear. An example of this is the research conducted by Eger et al. on "zero-defect manufacturing" [77,78]. In this context, the SoV approach is employed for modeling part variation [77,78]. Nevertheless, since the zero-defect approach is generally considered a clear quality management methodology [79], these two studies are not classified as PTVM. Nevertheless, it demonstrates the interdependent use of approaches from the two domains, and thus, a definite demarcation is challenging.

The research was also restricted to English and German language publications, so it is possible that uncategorized publications exist.

In conclusion, it can be stated that this review and the subsequent classification have resulted in a notable enhancement in the clarity of the subject matter pertaining to PTVM. The disparate designations and nomenclature of the approaches, coupled with the lack of a clear definition of a process-oriented view in tolerance management, rendered the subject area opaque and time-consuming to navigate. The necessity for expertise in this subject area further compounded the challenge. The review and classification should markedly enhance the efficiency of the familiarization process and facilitate the identification of the optimal approach for a given use case. By streamlining the familiarization process and offering a more comprehensive overview, the authors[‡] also anticipate that subsequent research in this domain will be more focused and can be more readily distinguished and categorized due to the proposed definition.

5. Conclusions and Future Research Directions

In the field of process-oriented tolerance and variation management (PTVM), there is a multitude of disparate methodologies, some of which employ the same nomenclature to describe different approaches or utilize disparate keywords to delineate the same methodology. However, these methodologies can still be categorized within PTVM. In order to provide a more comprehensive and coherent framework for the subject area, this paper proposes a definition of the term PTVM that is both generalizable and inclusive of all related approaches. Furthermore, the field should be clearly structured. For this purpose, a classification is proposed that comprises four classes in total: analysis of process chains, analysis of single processes, approaches for analyzing process chains and single processes, and overarching process-oriented tolerance management approaches.

Most of the publications considered can be classified in the class "analysis of process chains". One of the reasons for this is that one of the most important approaches to PTVM is the stream-of-variation approach with a corresponding state space model. This approach models the variation propagation in a multistage production system and is therefore an important component of a process-oriented approach. The second largest class, "analysis of single processes", includes much more diverse approaches. The remaining two classes, on the other hand, are rather subordinate niche classes with only three and two publications. The classification presented here is a first attempt to better structure the field. This classification approach can be continuously extended and improved by constantly analyzing and incorporating new approaches.

This research also identified several key areas for future research activities. From an organizational standpoint, PTVM merits greater consideration for the purpose of fostering inter-divisional networking and information sharing among divisions engaged in PTVM operations, encompassing product development, manufacturing, and assembly, among others. To ensure a meaningful integration of PTVM and associated data flows within individual company divisions, it is essential to delineate the key considerations at the organizational level to guarantee seamless integration.

Another important aspect is the modeling of further processes, including a detailed consideration of sub-processes. In the area of assembly, in particular, there are still many processes and sub-processes that need to be considered and modeled, as the individual nature of assembly, in particular, often requires specific processes and applications. Due to the large number of influencing factors and sources of variation, AI approaches are an important enabler, especially in the modeling of an assembly, but also generally in the modeling of production processes within the framework of PTVM, in order to be able to map even complex processes efficiently. The authors also see this as an important area for future research.

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Appendix A. Classification

Table A1. Classification of the publications.

Category	Author
Analysis of process chains	Hu 1997 [33], Jin 1999 [34], Lawless 1999 [80], Mantripragada 1999 [15], Suri 1999 [81], Ding 2000 [37], Ding 2001 [82], Ding 2002a [38], Ding 2002b [39], Ding 2002c [40], Camelio 2003 [83], Djurdjanovic 2003a [84], Djurdjanovic 2003b [43], Huang 2003a [85], Huang 2003b [42], Zhou 2003a[41], Zhou 2003b [44], Ceglarek 2004 [86], Huang 2004 [87], Huang 2004a [35], Huang 2004b [16], Kim 2004 [88], Ding 2005 [2], Djurdjanovic 2005 [89], Wang 2005 [47], Chen 2006 [90], Djurdjanovic 2006 [91], Ren 2006 [92], Shi 2006 [14], Djurdjanovic 2007 [93], Huang 2007b [94], Loose 2007 [45], Wandelt 2007 [95], Huang 2009 [96], Kong 2009 [97], Liu 2009 [98], Huang 2010 [99], Liu 2010 [100], Abellán-Nebot 2011a [101], Abellán-Nebot 2011b [12], Jiali 2011 [102], Shetwan 2011 [103], Abellán-Nebot 2012 [7], Abellán-Nebot 2013a [31], Abellán-Nebot 2013b [9], Abellán-Nebot 2013c [32], Du 2015a [104], Du 2015b [105], Liu 2015 [106], Zhang 2016b [72], Corrado 2017d [107], Müller 2017 [108], Yang 2017a [109], Yang 2017b [110], Chen 2018 [111], Du 2018 [51], Shui 2019 [112], Wang 2019 [113], Yacob 2019 [4], Benavent-Nácher 2020 [114], Heling 2020 [54], Hofmann 2020 [53], Jandaghi-Shahi 2020 [115], Yacob 2020 [17], Rezaei-Aderiani 2021a [116], Rezaei-Aderiani 2021b [117], Wang 2021a [48], Wang 2021b [118], Yacob 2021a [119], Yacob 2021b [18], Yacob 2021c [19], Huang 2022 [52]
Analysis of single processes	Praun 2003 [120], Shiu 2003 [121], Huang 2007a [71], Müller 2009 [122], Loose [123], Wärmefjord 2010a [49], Wärmefjord 2010b [5], Jiang 2012 [124], Müller 2012 [68], Pahkamaa 2012 [62], Wärmefjord 2013 [60], Zou 2013 [125], Franciosa 2014 [126], Polini 2015 [29], Corrado 2016 [24], Khodaygan 2016[65], Wärmefjord 2016 [64], Zhang 2016a [72], Corrado 2017a [25], Corrado 2017b [26], Corrado 2017c [27], Wang 2017 [127], Camuz 2018 [61], Corrado 2018 [128], Wieland 2018 [129], Abellán-Nebot 2019 [46], Lorenzoni 2019 [130], Mei 2019 [66], Müller 2019a [11], Müller 2019b [69], Polini 2019a [30], Polini 2019b [58], Polini 2019c [59], Junnan 2020 [73], McKenna 2020 [131], Müller 2020 [13], Shi 2020 [132], Corrado 2021a [55], Corrado 2021b [57], Mei 2021 [67], Polini 2021 [56], Tabar 2021 [63], Chung 2022 [133], Tabar 2022 [6], Franz 2023 [75], Moro 2024 [74], Peng 2024 [134], Zeng 2024 [135]
Approaches for analyzing process chains and single processes	Heling 2019 [10], Mende 2020 [36], Wartzack 2023 [1]
Overarching process-oriented tolerance management approaches	Andolfatto 2013 [76], Schleich 2013 [8]

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