Sandro Wartzack *Editor*

Research in Tolerancing

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Foreword by Luc Mathieu

One of the enduring challenges of modern engineering has been the management of variation in design and manufacturing processes. The journey from the beginnings of tolerancing to the current era of advanced tolerance analysis and synthesis methods has been marked by continuous innovation and the pursuit of robust design solutions. Today, the importance of tolerance management in ensuring product quality, performance, and reliability has never been greater. Nevertheless, ongoing research in the area of tolerance management is necessary to overcome upcoming challenges.

The book offers a thorough exploration of tolerancing practices, drawing on extensive research and practical experience. Its four parts encapsulate a comprehensive overview of the field of tolerancing, offering valuable insights into specific topics from this field. It covers foundational principles like robust design and advances into complex areas such as advanced tolerance analysis methods, non-geometrical key characteristics as well as process- and operation-oriented tolerance management. Each chapter delves deep into the intricacies of managing variations in engineering design and manufacturing.

What sets this book apart is its holistic approach to tolerance management, encompassing a wide spectrum of subject areas. By bringing together this collective research, the book not only offers a comprehensive overview of the current state of tolerance management but also anticipates the challenges and opportunities that lie ahead. Whether you are a practitioner seeking to enhance your understanding of tolerance management or a researcher exploring the applications of tolerancing, this book is a proper collection of knowledge and insights into this exciting topic. It is my sincere hope that the diverse perspectives and cutting-edge methodologies presented in these pages will inspire new directions of exploration and innovation in this dynamic field of tolerancing research.

Paris, France
March 2024

Luc Mathieu

Foreword by Rikard Söderberg

The area of tolerancing serves as a crucial bridge between product development and manufacturing. While customers expect high quality and precision, achieving this often necessitates the utilization of costly machinery and manufacturing processes, influencing the final price of the product. In the industrial landscape, tolerancing has always revolved around finding the balance between fulfilling customer demands for high quality and managing manufacturing costs.

The concept of tolerances in design and manufacturing has a long and evolving history. In the early stages of human craftsmanship, precision was limited, and products were often made by hand. There was little emphasis on standardized measurements or tolerances. The Industrial Revolution during the 18th–19th centuries marked a significant shift in manufacturing. With the advent of machinery and mass production, there was a growing need for standardization and interchangeability of parts. Interchangeability of parts did not only allow for efficient assembly but also for efficient repair and use of spare parts. Interchangeability became a key goal, leading to the development of standardization systems and the introduction of tolerances.

Today, tolerances are a critical aspect of design and manufacturing across various industries, from aerospace and automotive to electronics and medical devices. As a research field, the area of tolerancing has gained a lot of attention over the years, especially since the integration of computer-aided design and computer-aided manufacturing in the late 20th century. With more and more advanced digital technologies evolving, tolerancing will continue to play an important role in realizing the circular and sustainable economy of tomorrow.

The book you are about to read provides an overview of current subjects and research areas in tolerance management, targeting researchers who are working in the field of tolerance management or who wish to enter this domain. Experts from different areas of tolerance management will provide insights into their research fields, highlighting both the current state of research and emerging challenges.

Enjoy the reading!

Gothenburg, Sweden
March 2024

Rikard Söderberg

Preface

This book represents a culmination of years of dedicated research and collaboration in the field of tolerance management at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). The diverse and insightful contributions contained within these pages showcase the evolution of tolerancing research and the emergence of inspiring new approaches that have been developed over time. Therefore, I want to express my appreciation to all the former and current researchers from our tolerancing research group at Engineering Design (KTmfk), whose ideas and advancements in their respective fields in tolerancing have significantly contributed to the depth and breadth of this book.

I would like to extend my sincere gratitude to the writers of the Forewords, Prof. Rikard Söderberg and Prof. Luc Mathieu, whose expertise and perspectives contributed to the discussion of future directions in the field of research in tolerancing. A significant share of the knowledge presented in this book was influenced from the vibrant discussions and exchanges within the European Group of Research in Tolerancing (E-GRT) and CIRP Conference on Computer Aided Tolerancing, highlighting the importance of international cooperation and shared learning in advancing the field.

Furthermore, I wish to acknowledge the support of institutions such as the German Research Foundation (DFG) or the Research Association for Drive Technology (FVA e. V.) as well as the various collaborating companies from industry, whose continued commitment to research and innovation plays a crucial role in driving progress and excellence in tolerance management.

May this book serve as a resource and catalyst for further advancements in the dynamic and evolving landscape of tolerancing research. For a detailed exploration of the evolution of tolerancing research at Engineering Design (KTmfk) and a broad overview of the book's contents, please refer to Chap. 1 of this book.

Erlangen, Germany
March 2024

Sandro Wartzack

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Chapter 1
Research in Tolerancing

Sandro Wartzack

Abstract Product development and manufacturing face a variety of challenges resulting from today's dynamic markets, such as increasing complexity, rising quality demands, and required efficiency. Translating these challenges to tolerancing, there is a considerable need for new and innovative approaches to assist design engineers with the various tasks involved in this area. This textbook therefore focuses on current research topics in tolerancing and is aimed at researchers who are already working in this field or who plan to contribute new approaches to this interesting topic. This first chapter of Research in Tolerancing serves introductory purposes, first with a short introduction to the topic and the motivation for the book, second with insights into the exchange of tolerancing research between academia and industry, and third with an outline of the book's structure and contents. The latter summarizes the four main parts of Research in Tolerancing: Part 1–Interconnected Tolerancing Activities and Robust Design, Part 2–Advanced Tolerance Analysis and Synthesis Methods, Part 3–Tolerance Analysis Methods for Non-geometrical Key Characteristics, and Part 4–Process- and Operation-oriented Tolerance Management.

1.1 Introductory Remarks

In today's complex world of product development and manufacturing, tolerance management plays a crucial role in meeting the requirements for precision, quality and efficiency. The increasing complexity of products and production processes requires innovative approaches to ensure that tolerances can be effectively managed at all stages of the product life-cycle. The Research in Tolerancing textbook has been designed to provide an in-depth insight into the current research topics and areas of tolerance management and is aimed specifically at researchers already working in this field or planning to enter it.

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The textbook “Research in Tolerancing” is particularly notable for the extensive involvement of doctoral students from the Chair of Engineering Design at the Friedrich-Alexander-Universität Erlangen-Nürnberg. Since the early 1990s, our Chair has been intensively involved in research in the field of tolerance management and has contributed significantly to the development of theoretical principles and practical applications. A total of around 20 doctoral theses have been written in this field and an estimated 300 student theses have been supervised. The fundamental nature of the research work is reflected in particular by the fact that the scientists involved have mainly worked on research projects funded by the German Research Foundation (DFG). In addition to the fundamental research, practical software tools were also developed in co-operation with industry.

The research dynamics that have been established at the Friedrich-Alexander-Universität Erlangen-Nürnberg in the field of tolerancing since 1990 are particularly present in this book through the contributions of doctoral students. These young scientists contribute to continuing the tradition of cutting-edge research at the Chair and bring fresh ideas and innovative solutions to the anthology. Their contributions range from theoretical considerations to practical applications, giving the book a comprehensive perspective on tolerance management as a field of research. Thus, “Research in Tolerancing” functions not only as a compact compilation of the current state of knowledge and future challenges in tolerance management, but also as a platform for emerging talents to actively contribute to the shaping and further development of this fascinating field of research. The outstanding contributions of doctoral students and the increased awareness in industry highlight the increasing importance of tolerance management.

A significant event that emphasizes this development is the establishment of the Dimensional Management Forum at the beginning of the 2000s. This forum has established itself as a discussion platform for tolerance experts in the automotive industry. It served as a central body for the exchange of knowledge, experience and best practices in the field of dimensional management and tolerance management. The creation of this forum reflects not only the growing need to address the complex challenges of dealing with tolerances, but also the industry’s desire to work together to find solutions.

The contributions in the book thus reflect not only the progress of research at the university, but also current developments and discussions at an industry-wide level. Collaboration between the research community and industry is seen as crucial to advancing both scientific knowledge and practical applications. Overall, the combination of academic research and industrial practice in the book “Research in Tolerancing” illustrates not only the relevance of the topic of tolerancing, but also the increasing awareness and collective effort of the industry to jointly address the challenges in tolerance management and develop innovative solutions.

1.2 Tolerancing–Linking the Academia and Industry Perspective

Amid the growing awareness and increased collaboration between industry and research, new forms of tolerance management conferences and events have also emerged. In particular, under our leadership, the Chair of Engineering Design has successfully established the "Summer School Tolerance Management", an innovative format that covers various aspects of tolerance management. This Summer School presents a diverse mix of keynote speeches from industry experts, research presentations from leading institutes and short pitches from students presenting their work and findings in the field of tolerance management. This dynamic combination of industry, research and young academics provides a holistic view of current developments and challenges in tolerance management. A unique feature of the "Summer School Tolerance Management" is the integration of interactive workshops in which all participants work together on real-life tolerance management problems and develop solutions, see Fig. 1.1.

These practice-orientated sessions not only promote the exchange of knowledge, but also enable a direct transfer of theoretical knowledge into concrete applications. The workshops create a space for discussion, brainstorming and networking between experts, researchers and students. The introduction of this Summer School as a platform for comprehensive exchange and interactive learning emphasizes the innovative spirit of the Chair and our initiative to break new ground. This format not only promotes the further development of tolerance management as a field of research, but also helps to train the next generation of tolerance experts who can develop both theoretical knowledge and practical skills in this crucial area.

The increasing relevance of tolerance management and Geometric Product Specification in the industry is clearly reflected in the growing demand for training and guidelines. More and more companies are recognizing the importance of precise tolerancing and specifications according to the ISO GPS or ASME standards for their products. In this context, numerous companies used the opportunity to take advantage of training courses offered by our Chair or to have customized guidelines drawn up for the creation of tolerance specifications for internal company use. The training courses not only provide companies with a sound insight into the latest developments

Fig. 1.1 Impressions of Summer School Tolerance Management

and methods of tolerance management, but also enable them to apply this knowledge in practice. The practice-orientated training courses help employees to improve their skills in dealing with tolerances and ensure efficient implementation in development processes. The customized guidelines for tolerancing enables companies to establish clear and uniform standards for tolerance management. These guidelines not only take into account the specific requirements and processes of the respective company, but also integrate best practices and current research results from the Chair. Companies therefore benefit from improved tolerance management and increased efficiency in product development and production.

The growing number of companies drawing on the expertise of our Chair underlines its recognized position in the industry and confirms the effectiveness of the training and guidelines offered. This development shows that companies are increasingly striving to optimize their tolerance processes and stay at the cutting edge of research in order to remain competitive and deliver high-quality products.

The dynamics and advances in IT over the last decades have had a significant impact on research performance, especially in the context of tolerance management. Increased computing power has enabled the application of modern optimization methods and tools, which in turn have revolutionized the way tolerance analysis methods are carried out. Topics such as tolerance optimization have particularly benefited from new sampling methods, which have enabled a more precise and efficient analysis of tolerance chains.

Another decisive milestone is the emergence of innovative concepts such as Industry 4.0. The increased availability of data, particularly through the networking of devices and machines in production environments, has paved the way for innovative approaches in tolerance management. In this context, our Chair has developed the pioneering concept of Tolerance Management 4.0, see Fig. 1.2.

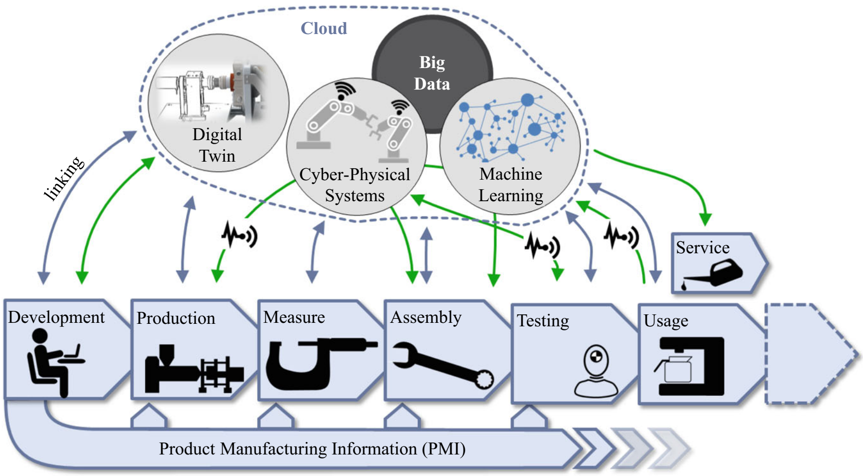

Fig. 1.2 Opportunities of Tolerance Management 4.0

It is characterized by the integration of individual component measurements and a tolerance analysis based on them. By utilizing this precise measurement data, components can be optimally paired with each other while at the same time using coarser tolerances. This approach not only enables more efficient production, but also helps to conserve resources and minimize costs without neglecting quality standards. Developments in the field of IT and the introduction of Industry 4.0 have thus contributed significantly to making tolerance management not only more precise, but also more effective and sustainable. The research achievements in this area, in particular the development of Tolerance Management 4.0, illustrate the ongoing contribution of our Chair to optimizing production processes and overcoming the challenges of the digital transformation era.

1.3 Outline of the Book

The contributions of doctoral students from our renowned Chair enrich the book with their fresh perspectives and innovative approaches. The diversity of topics covered by these emerging researchers not only reflects the broad research horizon of the Chair, but also helps to shed light on the latest developments and challenges in tolerance management.

The first part of the book is dedicated to a holistic description of the various interconnected tolerance management activities utilizing system modeling. Thereby, a consistent linking and automated derivation of Key Characteristics from requirements is addressed. These derived Key Characteristics form the basis for first tolerance management or robust design activities in early design process stages. It extends and frontloads the basic principles of tolerance management by linking aspects of tolerancing, quality management, robust design and product development, enabling its earliest possible application. This leads to an early robust and tolerance-compliant product design and forms a proper basis for in-depth tolerance management activities in later design stages.

Part two of the book focuses on advanced tolerance analysis and tolerance synthesis methods. The contributions in this part go beyond traditional methods and highlight complex topics such as tolerances in moving systems and the tolerance optimization resolving the conflict between costs and quality. The focus is not only on theoretical concepts, but also on practical applications and case studies, which requires dealing with further challenges, such as the high problem complexity and the associated high computing times.

The third part of the book focuses on non-geometric Key Characteristics in tolerance analysis. Specific challenges are addressed, including tolerances on rolling bearings and the validation of functional limit positions. The chapters in this part provide in-depth insights into tolerance analysis for complex and critical features that cannot be covered by geometric tolerances alone.

Finally, the fourth and last part of the book deals with process- and operation-orientated tolerance management. This part makes the transition from theory to practice by bridging the gap between product and process design. It considers aspects such as tolerance management in additive manufacturing as well as composite structures. In addition, the last chapter focuses on the automatic tolerancing information processing in Industry 4.0, where realistic considerations of the process characteristics are essential. For this, the advances in skin model shapes open up new possibilities, which are only briefly covered in this chapter, since numerous great publications exist on this topic. Thus, it becomes clear that tolerance management is not just a concept in product development, but also has a decisive influence on production and operational processes.

Bringing together these different perspectives and research areas in one anthology provides a holistic overview of tolerance management. Researchers and experts worldwide have the opportunity not only to learn about the current state of knowledge, but also to gain an outlook on future challenges and developments in this dynamic field. "Research in Tolerancing" thus serves as a valuable reference work for all those who wish to become involved in this important field of research.

Part I
Interconnected Tolerancing Activities and Robust Design

Chapter 2
Interconnected Tolerancing Activities and the Role of Key Characteristics

Dennis Horber, Stefan Goetz, and Sandro Wartzack

Abstract Products are nowadays characterized by rising complexity, so that companies need to adapt their development processes to resulting challenges. Transferring this need for adaption to the tolerancing domain, new approaches are expected to enable companies to tackle increasing quality demands and costs pressures. Resulting from that, a variety of tolerancing activities exist, which are closely interconnected with the product development process. Their application leads to several artifacts, which can be gathered in a digital thread weaving through the processes. As most of these approaches are document-centered, new progresses in model-based systems engineering offer unused potential to ensure traceable processes. This chapter therefore presents an approach for the model-based formalization of tolerancing activities to contribute to this digital thread. Furthermore, a holistic approach for a common key characteristic model is described, which is used along with the formalized activities. Due to their importance for tolerancing, key characteristics are a profound basis for enabling traceability and the approach ensures a thorough link. It includes the systematic and automated derivation of key characteristics from requirements using natural language processing, their further extension and prioritization.

2.1 Introduction

The current state of the art in tolerancing provides various approaches in order to successfully manage specific issues related to tolerances in the different stages of a product's life-cycle [1]. This variety of approaches is needed, due to the diversity

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of different challenges in the tolerancing domain and the ever increasing quality demands in today's markets. Thereby, the term tolerancing can have multiple meanings, as summarized by Dantan [2]. First, it describes the symbolic language used for geometric dimensioning and second, the set of activities, which enables the management of tolerances [2]. This chapter refers to the latter meaning.

Those activities can span from key characteristic (KC) definition, robust design and tolerance specification, allocation as well as analysis [1, 3]. With the application of tolerancing approaches, product developers and engineers can manage the later quality of a product. But challenges due to the growing product complexity, cost pressures, and new manufacturing methods occur, since multiple dependent aspects of the product life-cycle need to be considered [4]. The management of tolerancing activities therefore requires a targeted approach in the different development stages in order to produce relevant development artifacts and improve the development process, the realization process and lastly the product itself. The ratio between cost reduction and cost for change implementation thereby degrades with each stage of development, as described by Thornton [5], which results in the motivation for a frontloading of tolerancing activities into earlier stages of development [6].

In general, all the activities are required to improve the efficiency of the development process, since resources of a company are often limited and an efficient use can result in a competitive advantage [5]. Approaches within tolerancing activities often build on each other, but are not described accordingly and each produces different data or documents. This results in redundant information and interactions between steps in the process that are not well documented [7]. Motivated by that, a central product model that unites all the product information along the whole development process is crucial [8] to enable traceability along the process and data consistency. Those objectives are pursued in the field of model-based systems engineering (MBSE), where all the related data and information of a product with predominantly high complexity and its processes is stored in a single source of truth [9]. In tolerancing, approaches exist that refer to this idea [10], but do not fully utilize the potentials coming with MBSE, e.g., the several benefits such as improved accessibility of information, consistency, traceability and communication [11]. In this regard, Eifler et al. [12] remarked that the methodical development of robust products need to be aligned with MBSE to cover the numerous design trade-offs between various objectives, e.g., within the development of medical devices.

Focusing on the need for traceability and linking of data and activities, the results of a survey among German tolerance experts can be consulted [13]. The participants (n = 37) agreed on the statement that a structured provision and linking of all relevant information from tolerancing is important (84% thoroughly agreed, 16% mostly agreed) and that a linking of tolerancing information with their origin, such as KCs related to their respective requirements, is of interest (78% thoroughly agreed, 22% mostly agreed) [13]. Interestingly, none of the participants selected less or no agreement on these statements, which reflects the importance of this aspects perceived in industry. Moreover, previous studies with industry confirm the increasing need for a seamless data linking [14]. Therefore, the present chapter of this book focuses first on the digital thread through tolerancing (see Sect. 2.1.1) and the role of KCs (see

Sect. 2.1.2) then. The main section of this chapter (see Sect. 2.2) is divided into a brief introduction into the formalization of the wide variety of tolerancing activities in context of MBSE [7] (see Sect. 2.2.1), and the methodical creation of a holistic KC-Model that is required for the digital thread (see Sect. 2.2.2) due to the special role of KCs in tolerancing [15].

2.1.1 Digital Thread Through Tolerancing

The term "digital thread" in the engineering design context can be summarized according to Singh and Willcox [16] as the idea of linking information along the product life-cycle with a resulting data and communication platform. Goher et al. [17] and Alemanni et al. [18] describe the term concisely as a consolidation of all the data from requirement elicitation to retirement of the realized product in a digital model. Singh and Willcox [16] remark that the digital thread is more than a digital twin of a single product, since it is more than a digital representation of an existent product's life and can provide a foundation to enable a digital twin application [16]. According to Stark et al. [19], digital twins are therefore based on a product instance and the life-cycles of the product instance as well as its digital twin are closely related to each other. In tolerancing, such digital twins are for example used for geometrical variation management [20] and real-time geometry assurance [21]. Whereas the digital twins are mostly in form of a computational model or combined with simulation tools, the digital thread is required to provide information to a digital twin [16]. In this regard, Schleich and Anwer [22] proposed the term "tolerancing informatics", which comprises the information processing workflows for activities to manage tolerances throughout the product life-cycle. They conclude that the importance for industry and academia in tolerancing informatics will be increasing due to the rising digitalization in product development [22].

The digital thread is thereby closely related to model-based enterprises (MBE), which refers to organizations that apply modeling and simulation throughout production and the further product life cycle and manage its technical as well as business processes with that [23]. While several challenges need to be faced when transitioning to a MBE, as summarized in a literature study by Goher et al. [24], one integral prerequisite is the thorough integration of the model-based definition (MBD) [25]. Motivated by an improvement in consistency [18], MBD focuses on the integration of product manufacturing information in a CAD model as well as geometric dimensioning and tolerancing information [25]. Therefore, it can be understood as a 3D digital product model that includes required specifications of the product. A MBE approach makes use of these models rather than documents [26], but although early adopters exist, e.g., in the manufacturing industries for aerospace and automobile, the use of the two-dimensional drawing is still common [17]. In their study with three industry use cases, Hedberg et al. [26] conclude a 74.8% reduction in cycle-time when working model-based instead of drawing-based and remark that other benefits can be achievable, such as better product data quality and thus an improvement in product quality [26].

This shift from documents to models is an integral part of MBSE, where the digital continuity is strived for and describes the network of all activities in the development process, necessary data and models with a continuous flow of information [9]. Where the CAD model is the foundation in MBD and MBE, models in MBSE can be a wide variety of product or process representations and serve as integration enabler as well as predictor of behavior [27]. Historically seen, the main purpose of models in MBSE were the translation of requirements to design, but by now they are more holistic to enable interdisciplinary approaches [28]. In the given context of tolerancing, this enables a thorough perspective on the whole life-cycle and spans across all its stages. The following subsections go more into detail about the variety of activities and data along the digital thread through tolerancing first (see Sect. 2.1.1.1) and subsequently about challenges and opportunities induced by MBSE (see Sect. 2.1.1.2).

2.1.1.1 Variety of Tolerancing Activities and Data

The fundamental development process of products is characterized by various activities along the different stages and many different models with varying degree of detail exist for the purpose of structuring [29–34]. Thereby, the linkage with corresponding data is crucial [35], which enables the proper application of relevant methods and software [36]. Bridging to tolerancing, the corresponding activities are often poorly located in the underlying development process [37] and the interactions of different activities remain unclear. Therefore, some surveys include the localization of tolerancing activities within the product development process [1, 14, 38]. Activities early in this process often focus on robust design [39–43], which is based on the Axiomatic Design proposed by Suh [39]. Their results include process parameters and their contribution to customer satisfaction [44], e.g., in the context of automotive body parts manufacturing [45]. In the tolerancing domain, the link of different stages along the life-cycle is common and required due to their broad impacts [46], which is demonstrated by several approaches [37, 47, 48]. To enable this linkage, comprehensive models are needed, such as the integrated tolerancing process [49] or the mapping of the Computer-Aided Tolerancing [50]. Concluding from that, activities in tolerancing go far beyond the traditional tolerancing tasks such as the final tolerance specification for manufacturing and assembly.

As a result of the activities in tolerancing, a variety of product information and data in different formats is generated. Therefore, a profound platform is required that enables the storage and provision of data along the life-cycle, which is the task of product life-cycle management (PLM) [51]. With regard to tolerancing, Saunders et al. [52] summarize the operational context of PLM as the capturing and organization of data, allocation and optimization of resources, verification and validation of activities, and enabling of communication in case of changes. With a special focus on measurement, they conclude that PLM can support the dimensional measurement workflows and decision-making in this context [52]. The application of digital twins is a suitable example in this regard due to their dependence on the linkage of data, e.g., from real manufactured parts with the digital product model [14, 20, 22, 53]. For the provision of data and knowledge, the use of ontologies is feasible [54], e.g., as applied for manufacturing knowledge sharing in the context of PLM [55]. Besides that, activities may also share information directly and therefore, neutral formats are required for a standardized exchange of information [56]. Such being QIF or STEP [57, 58], whereas the latter can be specified by different protocols, e.g., STEP AP 242, which enhance the information capability of the format [59], thus fostering a consistent model-based representation. However, the focus is commonly on the modeling of the final tolerance information instead of the consistent mapping of the variation management process leading to this information.

The trend towards increasing product complexity impacts the activities within the product development process as well [9] and requires a shift from document-centered development [60]. In the context of tolerancing, Schleich and Anwer [22] mention that MBD is at least required for this purpose. By that, MBD offers potential for an automatic processing of tolerance information and also for linkage of all tolerancing related information across the product life-cycle [22]. Other approaches exist that likewise focus the consistent mapping of product information to CAD models, such as functional information [61]. With the progression of the development process, more details about the geometry is present and therefore the early use of models that enable the semantical description of the toleranced geometry is feasible [62, 63]. Other approaches combine specific models from tolerancing, e.g., the IPPOP product model and GeoSpelling tolerance model [64]. Even though the associated process intends a progressive detailing of geometry and tolerancing, the concrete activities in this transition are not explicitly defined [65].

Concluding from that, a variety of activities, associated models and data that is relevant for different aspects of tolerancing in the product life-cycle exist and, according to Schleich and Anwer [22], first steps towards realizing the digital thread are present. The focus of tolerancing thereby often lies on the manufacturing domain [22], but a thorough link between tolerancing in product development, process planning and manufacturing is required [66, 67]. The vision of a holistic linkage in the model requires the derivation of KCs from general product requirements [68] in order to use this information in further approaches, such as tolerance analysis [69, 70] and enable traceability. This lastly reveals potentials for automating activities and single steps in tolerancing [71].

2.1.1.2 Challenges and Opportunities Along with MBSE

Resulting from the different approaches enabling an initial digital thread through tolerancing, challenges and opportunities can be concluded. Those can be relevant for the development of new approaches that expand the current focus of specific solutions to a broader view and a better traceability. In this regard, the advances in the field of model-based development and MBSE enable new approaches, such as the operation of digital twins [20]. In a study conducted Wärmefjord et al. [14], remaining challenges to achieve holistic data linking in tolerancing, e.g., consistent documentation, updating and utilization of data in a single life-cycle model, were identified. The latter requires a proper integration of data into the development process [14] and it can be derived that there is still unused potential due to those challenges not being solved. With regard to MBSE, Eifler et al. [12] conclude future research tasks for robust design, e.g., that methods need to support cross-disciplinary engineering and by that, integrate knowledge from mechanical, electrical and software engineering as well as from data scientists. This is a main reason for the application of MBSE, since the increase in complexity requires the different engineering disciplines to interdisciplinary work together on the aspects of development, manufacturing and other life-cycle stages [9]. By that, the aforementioned challenges can be solved and turned into opportunities [9] and benefits of MBSE, like cost and risk reductions, are realizable [11]. Henderson et al. [72] list various empirically studied and assumed benefits benefits for MBSE [73]. It is therefore necessary to focus new approaches towards tangible benefits [73], e.g., easier accessibility and increased availability of development data through the "single source of truth" [72]. As mentioned, this is referred to as the digital continuity [9]. This enables, for example, results from early development, such as the definition of tolerance requirements, to be used consistently in subsequent stages [7].

When it comes to utilizing the digital continuity, data can be systematized along the process and can successively retrieved for approaches, which is beneficial due to the rising availability of data in later stages and the abundance of data leading to complexity [7, 74]. But a major challenge is the diversity of data that is produced within the different stages of development. For example, early stages are characterized by qualitative and abstract models, e.g., concept sketches, and differ in their information content and their level of detail compared to models from later stages [13, 75]. But studies come to conclusion that the thorough linkage of data from product development with the tolerance domain is still not achieved [76]. Thus, approaches should focus more on a holistic linkage and include the processes that produce this data instead of just representing existing information. But currently, several approaches just cover single tolerancing activities [10]. Moreover, thorough links along the development process could lead to the detection of further relations [65] and thereby gaining more knowledge about the interrelationships and supporting their handling [77].

Besides the focus of approaches, a major bottleneck is the lack of a common language, as remarked by Morse et al. [74] and Aderiani et al. [25]. With the advances in the context of model-based definition [25], a contribution to linking tolerancing data through 3-dimensional PMI is achieved, but it focuses mostly on the link between data. Therefore, the potential to relate the activity as a source of data production and other parts of the development process remains unused. Since the parallels of the digital thread through tolerancing and MBSE, common languages in this field were already applied in tolerancing. For example, the Unified Modeling Language (UML) [64, 68, 78] or the Systems Modeling Language (SysML) [7, 10, 43]. The interest in industry of applying MBSE and the associated languages [9] offfers therefore the opportunity for new approaches in tolerancing to make use of this languages.