Model-Based Unification of Various Design Aspects for Multi-Criteria Tolerance Optimization

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Abstract

Technical product development requires balancing diverse, often conflicting requirements through highly integrated and iterative design processes. The Design for X concept addresses multiple design aspects systematically, with tolerances crucially affecting product quality and lifecycle performance. However, tolerancing usually only considers aspects of functionality and manufacturabilty, neglecting further Design for X viewpoints, like lifecycle costs. In order to overcome the current hurdles in integrating these different viewpoints, this paper proposes a model-based approach leveraging Model-Based Systems Engineering and Product Lifecycle Management for tolerancing. By integrating simulations, design aspects, and requirements into a unified model, the approach enables targeted, traceable tolerance optimization. A drone development case study illustrates the approach's practical application.

Keywords

MBSE, PLM, Tolerance Optimization, Multi-Domain Simulation, Design for X

1. Motivation

Technical products must be developed considering a wide range of sometimes conflicting requirements, making structured and integrated development approaches essential. This is particularly important as product development is an iterative process in which design decisions are continuously revisited to satisfy technical, economic, and ecological goals. Design for X (DfX) is an established concept for this purpose that systematically addresses a variety of design aspects, such as quality, functionality, and manufacturing [1]. Tolerances play a central role here, as they influence a variety of these design aspects. Even slight deviations from the ideal geometry can affect product properties throughout the entire life cycle, e.g. by increasing the friction in hinges [2]. To meet the requirements, it is important to understand the relationships between possible deviations and their effects. Given the large number of affected design aspects, a systematic and consistent integration of tolerances in product design is necessary to avoid unintended trade-offs. Therefore, model-based approaches such as Model-Based Systems Engineering (MBSE) are suitable to overcome the associated challenges, especially in the case of complex products. They enable the structured mapping, traceability, and consistent integration of requirements, functions and structures across design aspects [3]. The model-based linking of tolerances with various design aspects is therefore not only a methodological advance, but also a necessary prerequisite for defining tolerances in a targeted, traceable, and quality-assured manner, thereby providing holistic support for product development.

Building upon these considerations, this paper proposes an approach for the model-based linking of tolerances to design aspects. It is organized as follows: Chapter 2 discusses the state of the art. Chapter 3 elucidates the necessity for research, while Chapter 4 delineates the approach. Finally, a case study is presented in Chapter 5 and a conclusion is given in Chapter 6.

2. State of the art

The following chapter examines the current state of the art in DfX and MBSE as key enablers for systematic tolerance integration. This provides the foundation for identifying existing gaps and deriving the proposed approach.

2.1. Design for X

In order to address a variety of design aspects concurrently, the established DfX concept is utilized. The scope of DfX extends across the entire product lifecycle, covering phases from conceptual design to recycling. As Huang [2] highlights, DfX plays a crucial role in managing trade-offs at the product, process, and system levels. By integrating a wide range of disciplines, DfX provides a structured foundation for informed decision-making throughout product development. To ensure a consistent and goal-oriented development process, these diverse aspects must be considered in parallel rather than in isolation. In this context, Hubka [4] describes DfX as a systematized body of design knowledge that enables the targeted shaping of product properties. Holt and Barnes [5] classify DfX evaluation methods into four main categories: qualitative guidelines, quantitative metrics, feasibility checks, and software tools that implement these assessments. To support such evaluations, simulations from different engineering domains are used. Examples include assembly simulations [6], finite element simulations [7], and manufacturing process simulations [8]. To apply DfX effectively, evaluation tools help engineers assess and improve design alternatives throughout the development process [5].

However, physical components are inherently subject to variations due to inevitable imperfections in manufacturing processes. This makes the consideration of tolerances essential.

Tolerances specify the permissible limits of deviation from nominal geometry and link the idealized design with its physical realization. [9] Tolerances have a substantial impact on a variety of design aspects. Even minor deviations can affect mechanical strength, assembly accuracy, functional performance over the lifecycle, and production costs [2]. Taguchi et al. [10] demonstrated early on that tolerance design plays a crucial role in product quality and cost optimization, highlighting the value of variation control and robust design methodologies. Wartzack et al. [11] proposed a lifecycle-oriented approach to tolerance management. Their method considers the effects of deviations not only during manufacturing processes but also throughout operation. It addresses design aspect concerns including quality assurance, manufacturability, assembly processes, and system performance. Studies have further advanced this perspective. Hoffenson and Söderberg analyzed the influence of tolerances on environmental impact, cost efficiency [12], and ergonomic performance during assembly [13]. Their research introduces quantitative methods to optimize tolerance decisions with respect to multiple, sometimes conflicting, objectives. Initial efforts toward establishing consistent system-level integration of tolerances across Design for Quality have also been reported [14].

2.2. Model-Based Systems Engineering

To handle the growing complexity of product development, MBSE has emerged as a promising methodology. Friedenthal et al. [3] define MBSE as a model-centric approach that replaces document-based development with formal system models. These models unify requirements, functional design, architecture, and validation strategies in a coherent framework. MBSE supports traceability, enables early verification, and promotes consistency across engineering domains. These capabilities are particularly valuable when integrating tolerance considerations into broader system models. Recent research has begun to embed tolerance information directly within MBSE frameworks. Benavent-Nácher et al. [15] introduced an extension of the SysML that explicitly captures tolerance specifications. This enhancement allows tolerance data to be reused in downstream processes such as manufacturing processes [16]. To fully leverage the traceability and linking capabilities offered by the MBSE approach, Kranabitl et al. [17] developed a concept that enables the systematic connection of domain-specific models through the system model. Building on this, Bruggeman et al. [18] propose a framework that establishes a direct link between MBSE and Multidisciplinary Design Analysis and Optimization (MDAO). In their approach, formalized, model-based requirements are embedded directly into the optimization process. MDAO workflows are derived from verification methods, allowing for requirement-driven optimization.

3. Research need

The integration of various design aspects with MBSE provides a promising foundation for holistic and consistent tolerance management across the product lifecycle. While initial research has demonstrated the potential of such linkages [17], the systematic and scalable implementation of tolerance-related information within system models remains an unresolved challenge, particularly in the context of complex products.

Key obstacles include the coordination of competing design objectives, the identification of interdependencies between tolerances and various design aspects within system models, and the establishment of a consistent and automated data flow. These challenges must be addressed in order to make full use of the traceability, consistency, and multi-domain capabilities that MBSE offers. This paper therefore proposes a model-based approach for linking tolerances with relevant design aspects. The guiding research question is:

How can tolerances be represented and systematically integrated across a variety of design aspects using model-based methods to enable continuous tolerance optimization throughout the product development process?

The proposed approach aims to enable a solid and consistent definition of tolerances that reflect and balance various design aspects, thereby supporting informed trade-offs and the targeted adjustment of design aspects based on cross-disciplinary evaluation criteria.

4. Approach for model-based unification of various design aspects for tolerance optimization

This section presents the conceptual framework of the proposed approach, which builds on the core elements of a system model as illustrated in Figure 1. It enables the structured representation and linkage of relevant product information through a comprehensive system model. In this context, resources, requirements, simulation models, and product geometry are integrated into the system model. To support this integration, modeling is carried out using established systems engineering languages such as SysML or Capella, which provide the necessary constructs for representing complex system relationships.

Beyond the integration of information, the approach also considers the embedding of the system model within a proprietary software environment, such as a Product Lifecycle Management (PLM) system. This raises the fundamental question of which types of information should be stored directly in the system model, and which should be referenced or linked from external, software-managed sources. Clarifying this distinction is essential to ensure consistency, avoid redundancy, and maintain a clear separation of responsibilities between the system modeling and the overarching data management infrastructure.

For example, the integration of tolerances into the system model can be realized using the SysML tolerance profile proposed by Benavent-Nácher et al. [15]. However, individual measurement points required for verifying these tolerances are difficult to incorporate directly into the system model. In such cases, linking this verification data to a PLM system is a more appropriate solution, allowing for efficient management and traceability of detailed product data beyond the scope of the system model itself.

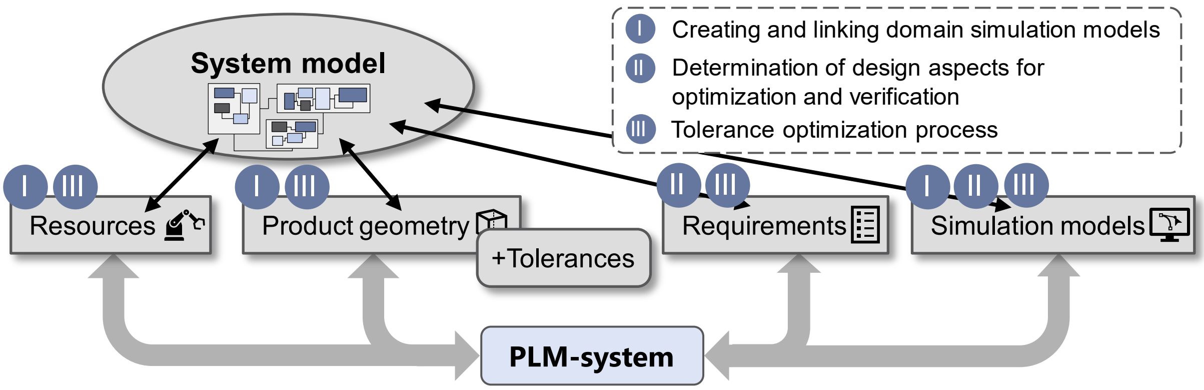

Figure 1: Necessary components of the system model for corresponding elements of the approach

The approach is divided into three main stages. Chapter 4.1 focuses on the creation and connection of simulation models from various engineering domains with the system model and PLM-system, using available resources and geometric data. Based on these simulations, Chapter 4.2 determines relevant design aspects, which are then validated against defined requirements. In the final step, presented in Chapter 4.3, these design aspects serve as the basis for tolerance optimization. Finally, the approach is demonstrated using a drone development scenario to ensure practical relevance.

4.1. Creating and linking domain models within the system model

A model-based linkage between various design aspects must first be established. A conceptual representation of this linkage of the geometry model, resources and simulation models within the system model and PLM-system is shown in Figure 2.

For this purpose, the concept introduced by Kranabitl et al. [17] is adopted. In this approach, the geometry model from the system model serves as the input model. Simulation methods (e.g., finite element analysis) are applied using additional resources such as calculation models and parameters that are also derived from the system model. The resulting output from each link is a domain-specific simulation model within the proposed framework. Domain experts are initially required to create these simulation models by incorporating their specific knowledge and expertise. Alternatively, there is potential to generate and utilize output models directly from the system model in an automated manner, as explored by Wilking et al. [19].

Once created, the simulation models are linked back to the system model, enabling their reuse in subsequent steps. This integration ensures consistency in analysis and optimization by maintaining all data and relationships within a unified system model. The proposed approach extends the original concept of Kranabitl et al. [17], which emphasizes a unidirectional flow of information from the system model to simulation models. In contrast, the extended approach establishes a bidirectional connection between simulation models and the system model. This enables both input and output data from simulations to be accessed and utilized automatically, thus enhancing model consistency and reducing manual effort across domains.

In addition to the system model, the PLM system is considered as an alternative or complementary platform for linking simulation, geometry, and resource models. This is particularly relevant for managing data that is not directly modeled within the system model, such as large datasets or version-controlled simulation results. However, establishing this connection requires appropriate software integration between the system modeling environment and the PLM infrastructure. Such technical interoperability is essential to ensure the consistent and traceable management of models and data across both platforms.

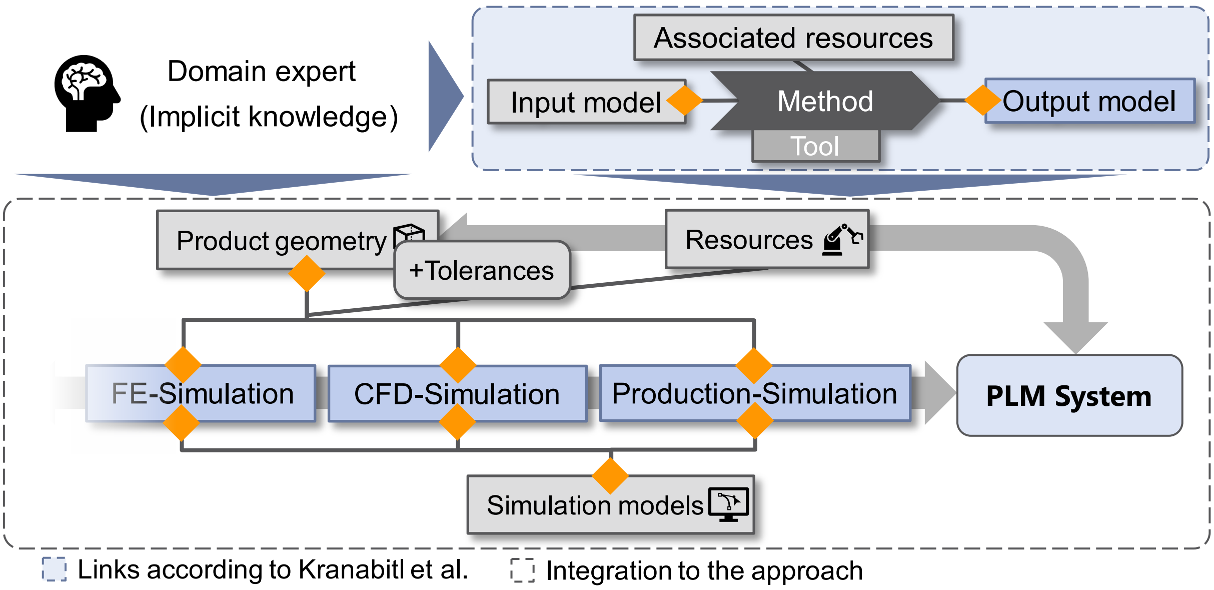

Figure 2: Linking the geometry model to various simulation models using expert knowledge according to Kranabitl et al. [17]

4.2. Determination of the design aspects from the simulation models

Based on the developed and linked simulation models, various design aspects can be determined, which serve as evaluation criteria for various design aspects, as shown in Figure 3. These design aspects can be directly associated with specific design objectives and used to assess whether a product meets defined quality, performance or sustainability requirements. In many cases, these design aspects result from the combination of multiple simulation models. For example, evaluating product functionality may require simulations of mechanical stress as well as wear behavior. It is therefore essential that domain experts define the necessary design aspects during model creation and link them to the relevant system requirements.

To support evaluation and optimization, design aspects must be compared with existing requirements. A central challenge in this step is that requirements are often available in heterogeneous formats and with varying levels of formality and granularity. For automated processing, they must be available in a standardized, machine-readable format. This can include Boolean statements or numerical threshold values. Existing methods enable the transformation of informal requirements into formalized representations using, for example, AI-supported techniques such as large language models (LLMs) [20]. By using modeling languages such as Object Constraint Language (OCL), these formalized requirements can be integrated into the system model and automatically compared with simulation results [21]. This allows consistent validation of requirements and supports the subsequent optimization of tolerances.

When using the design aspects for further optimization, it is essential that these design aspects are comparable with one another. One solution is the use of a unifying metric that combines qualitative aspects and quantitative values with different units into a single comparable score. The metric is based on the principle of multi-criteria evaluation [23] and can be adjusted to individual preferences and priorities by applying weighting factors to the different design aspects. This approach is particularly valuable in automated optimization processes, where decisions must be made without human intervention. In cases involving multiple conflicting objectives, a multi-objective optimization would typically yield a Pareto-optimal front. By applying a unifying metric, the multiple objectives can be aggregated into a single scalar value, enabling the identification of one optimal solution. This simplification not only reduces computational complexity but also supports seamless integration into automated pipelines. [22]

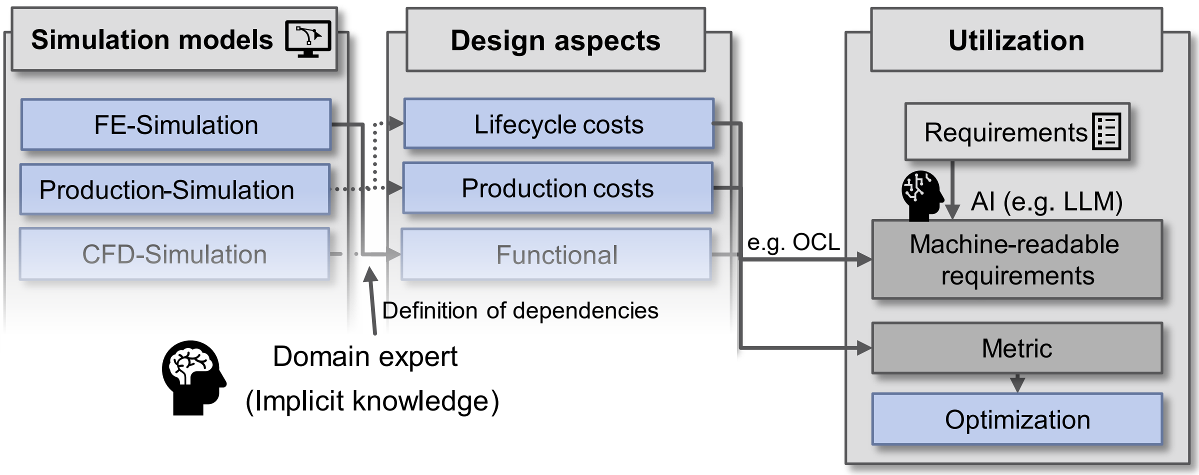

Figure 3: Determination of the various design aspects for further use for requirements verification and optimization of tolerances

4.3. Optimization process for tolerances

The process of tolerance optimization is structured into the components: Given, Optimization Parameters, Variables, Steps, Constraints, and Objectives [24], as illustrated in Figure 4.

As a starting point, the geometry and the required resources are defined. These elements form the basis of the optimization and are integrated into the system model and PLM-system. The available resources can serve as optimization parameters. This is particularly relevant when multiple alternatives exist for enriching simulation processes or when production-related boundary conditions influence achievable tolerance precision. For example, depending on the selected manufacturing process, different levels of geometric accuracy may be feasible, making different resources a significant factor in the definition of tolerance limits. The optimization variable in this approach is the set of geometric tolerances. These are directly linked to the geometric model e.g. via the applied tolerance profile for SysML by Benavent-Nácher et al. [15], ensuring their consistent inclusion in the optimization process. The active steps in the optimization consist primarily of the domain-specific simulation models. Instead of using the idealized nominal geometry as input, geometrical variations within the defined tolerance ranges are generated and simulated. These variations are not created independently, but are based on geometry imported and managed within proprietary software tools, such as Teamcenter VisVSA. This provides statistical information about the effects of the tolerances on the design aspects. From each simulation model, design aspects are derived, which are then evaluated. As described earlier, these design aspects can be compared to formalized requirements. In the optimization context, these requirements act as constraints, meaning they must be satisfied in all valid solutions. If constraints are violated, the corresponding tolerances must be adjusted. The optimization objective is defined by a weighted value derived from the unifying metric.

The optimization takes as input the system-integrated geometry, initial tolerance values, and relevant resource information such as manufacturing capabilities. Based on simulation results and formalized product requirements as constraints, the optimization algorithm (e.g., ant colony optimization [25]) outputs an adjusted set of tolerances that meet all constraints while minimizing a weighted objective derived from design aspects.

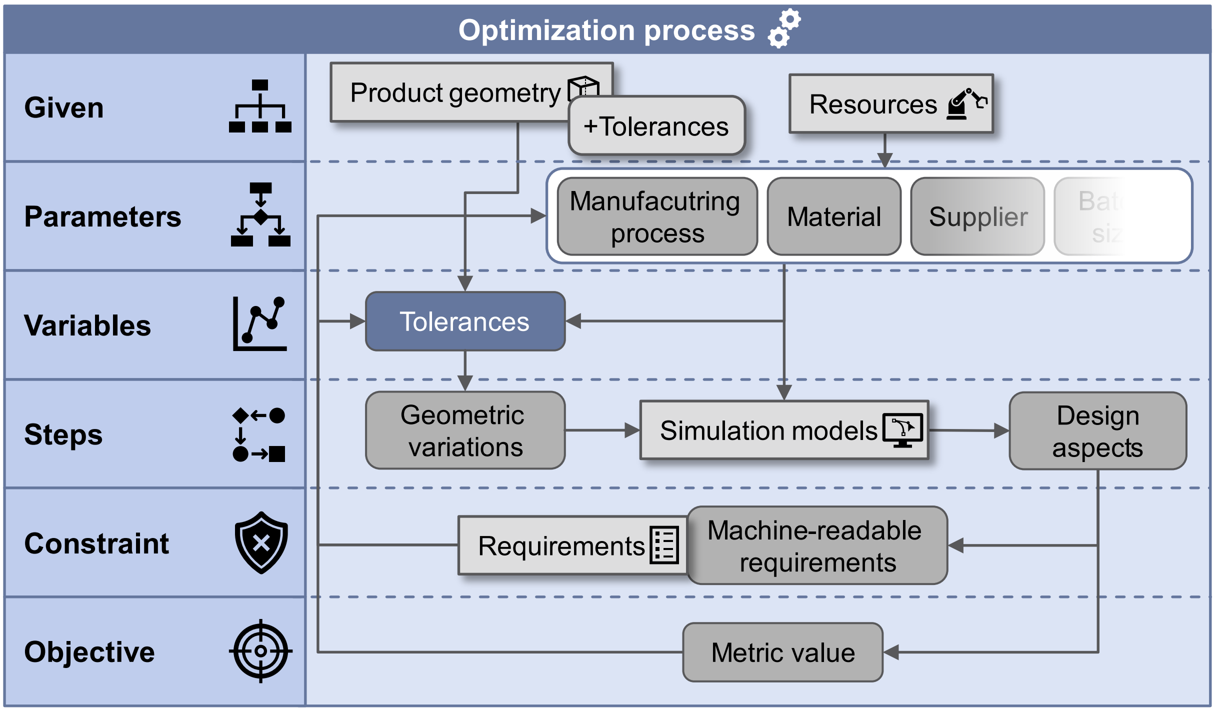

Figure 4: Tolerance optimization process

5. Application

The proposed approach is illustrated by applying it to the development of a drone arm as shown in Figure 5. A critical feature in this example is the integrated ventilation opening in the drone arm which must meet precise dimensional specifications to ensure the reliable operation of the drone's control unit. The dimensions of this opening must neither exceed nor fall below certain limits to guarantee sufficient airflow and prevent overheating. Economic considerations also play a significant role since the total production cost is capped at 25 €. Tolerances have a decisive impact because tighter tolerances usually increase production costs while looser tolerances risk product failure and scrap.

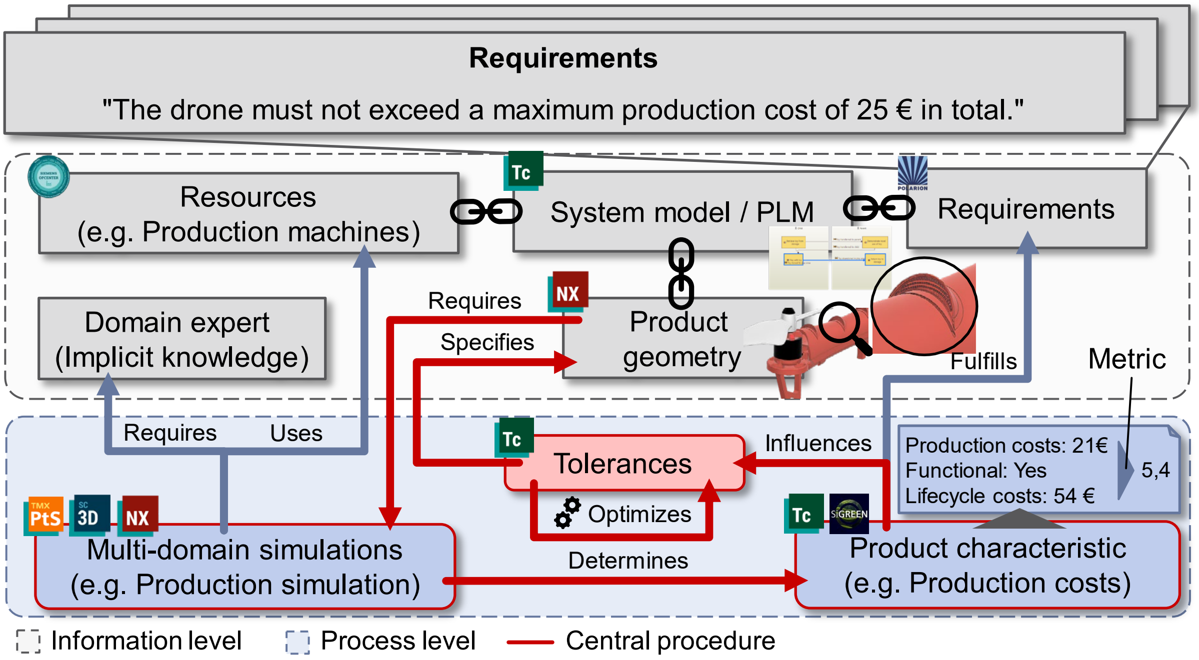

Figure 5: Model-based approach for linking various design aspects with tolerances

All relevant information including product requirements, available production resources such as machine selections and detailed geometric data with tolerances is managed within a comprehensive system model and PLM-system. Domain experts develop and link various simulation models including production simulations to estimate production costs and CFD simulations to evaluate functional performance. These simulations are based on slightly varying geometries generated within the defined tolerance ranges capturing realistic deviations via statistical sampling methods. The design aspects derived from these simulations serve as quantifiable metrics reflecting compliance with various design aspects. By expressing requirements in machine-readable formats using modeling languages such as OCL these design aspects can be reused and automatically validated enabling a systematic and automated assessment of requirement fulfillment. The tolerance optimization process is based on this integrated data and is divided into the following key components. First, the drone geometry and available resources with simulation parameters (e.g., production machines) serve as the given simulation basis. The optimization variables that are optimized are the tolerances of the drone geometry. The constraints of the optimization are specified by the requirements. For example, maximum production costs of 25 € must not be exceeded. Finally, the design aspects can be used as objectives of the optimization process through the unifying metric. Proprietary software (e.g., Teamcenter or SiGREEN) can be used to integrate the design aspects into the linked model. The unifying metric consolidates multiple often conflicting objectives into a single evaluation score. In this example, production costs may conflict with performance or CO_2 emissions, for example, in that tight tolerances increase production costs but improve performance and reduce CO_2 emissions through less scrap, while wide tolerances reduce production costs but decrease performance and increase CO_2 emissions. This metric enables the use of optimization algorithms such as ant colony optimization [25]. By reducing the multiple objectives to one value the process ensures there is at most one optimal solution for an automated optimization.

This example illustrates the conceptual application of the proposed approach. It shows how geometry data, resource models, simulation inputs, and requirements can be systematically linked within a unified model to support tolerance-related design decisions. The integration of tolerance information and simulation outputs enables informed trade-offs early in the development process. The resulting model functions as a central reference across domains, supporting traceability and reuse. As outlined in Chapter 3, key challenges remain - especially in systematically integrating tolerances across various design aspects and handling diverse requirement formats. The proposed approach offers a conceptual framework that enables such integration in principle but does not fully resolve these issues yet. It lays important groundwork but requires further development and validation. Thus, while the research question is conceptually addressed, practical implementation and comprehensive automation remain open for future work. A critical point that must also be considered is the large number of simulation runs required. These lead to high computing power requirements, which potentially slows down the optimization process.

6. Conclusion and outlook

This paper presented a conceptual model-based approach for systematic tolerance integration and optimization across various design aspects within a unified model. By linking geometric data, production resources, simulation models, and formalized requirements, it enables automated, transparent tolerance optimization. A theoretical drone arm case study showed how technical, cost, and sustainability constraints can be considered simultaneously, demonstrating the practical relevance and potential of the approach. Multi-domain simulations support comprehensive evaluation and trade-offs between technical performance, cost, and sustainability.

The approach can be implemented step-by-step by integrating system models with existing data platforms and linking simulation tools via standardized languages. This allows starting with selected design domains and gradually expanding integration for consistent, traceable tolerance management. Early pilots across engineering fields can validate and improve the method, promoting more efficient, cost-effective, and sustainable product development through model-based decisions.

Future work will focus on three areas: First, improving integration of tolerance-relevant information in the system model by classifying relevant types and defining information flows. Second, advancing automation through AI-supported detection and generation of missing information. Third, enhancing reusability of model-based information via a unified metric that consolidates diverse evaluation criteria for model-driven optimization amid competing requirements.

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