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A new approach to first tolerance evaluations in the conceptual design stage based on tolerance graphs

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Abstract

Tolerancing is commonly performed in late design stages, in which the product geometry is fully defined. However, this often leads to high manufacturing costs or expensive design changes. Therefore, motivated by the idea of frontloading, a new approach for first tolerance evaluations in conceptual design stages is developed, which enables a first tolerance specification and analysis based on the few geometry data available. Together with semantic information of the interface notations of adjacent parts, graphs including relevant geometry elements and tolerance information are generated. These graphs support designers with a first assessment of tolerance situations before the geometry is finally defined.

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1. Tolerance management in product development

Real products inherently differ from their intended nominal geometry due to imperfections in manufacturing processes. To fulfill geometrical as well as functional requirements, the inevitable geometrical deviations are restricted by tolerances [1]. However, the striving for fast and efficient product development processes forces designers to employ methods for the virtual verification of tolerances [2, 3].

These methods enable an early function validation and help developing robust designs insensitive to variation [4]. Despite the fact that tolerance considerations in early design stages are the only way to achieve robust products, tolerancing is usually performed in later design stages after the nominal dimensions have been fixed [5, 6]. This contradictory phenomenon arises from a lack of methods applicable in early design stages [7].

Motivated by this lack, appropriate methods enabling a concurrent product and tolerance design are studied in the framework of an ongoing research project focusing on tolerance considerations in conceptual and embodiment design stages according to Pahl/Beitz (see Fig. 1) [8]. Particularly, this paper presents an approach to first tolerance evaluations in the conceptual design stage based on tolerance graphs.

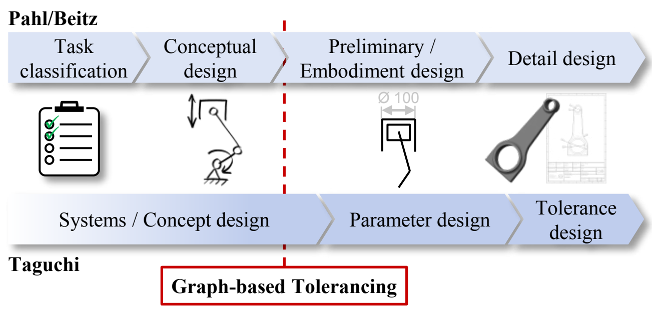

Fig. 1. Classification of graph-based tolerance evaluations in the design process according to Pahl/Beitz [8] and Taguchi [9]

In this phase of product development, even though the product structure and the solution principle are already defined, there is a lack of geometry information, which is fundamental for most tolerancing activities. However, at the same time, this lack opens the chance for quick design changes and is a major challenge in early tolerance consideration.

The paper is structured as follows. In the next section, related works concerning methods for the tolerancing in early design stages as well as the state of the art regarding graph-

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based tolerancing approaches are discussed. Thereafter, the novel approach to first tolerance evaluations in the conceptual design stage based on tolerance graphs is explained and the main steps of this method are detailed in sections 4 and 5. Finally, a conclusion and an outlook are given.

2. Related work and state of the art

The potential and challenge of tolerance considerations in early design stages is widely recognized as one of the main topics in tolerancing and robust design research. In this context, Taguchi is considered as a pioneer in introducing a robust design method, which nearly covers the complete product development process (see Fig. 1). It starts with the system design and proposes the consideration of potential manufacturing variations already during the development of product concepts [9]. For this purpose, the influence of input factors on the product's functionality is to be analyzed [4]. A possible criterion is the location scheme [10]. In this context, Suh's axiomatic design recommends reducing the number of parameters affecting functionality [11]. Alternatively, so-called Key Characteristics, which are decisive for the fulfillment of a function, can be chosen from the numerous affecting parameters [12].

In general, the need for function-oriented tolerancing is indisputable [13]. To meet this demand, Bradley and Maropoulos introduced a product model for a continuous administration of data from functional features in conceptual design to tolerancing in detail design [14]. Anselmetti presents a more consequent and extensively automated realization of functional tolerancing [15]. However, the approach requires a fully defined CAD-model [16]. In a similar fashion, Armillotta introduced an automated tolerance specification method based on functional and assembly features [17]. Besides feature-based methods, semantic information can be used for facilitating the tolerancing process [18, 19].

Another widely spread approach, mainly for the visualization of tolerances, is the use of the graph theory. These methods use graphs to represent the structure of a mechanical product and to clearly visualize the parts, the part features and their interdependencies [15, 20]. In contrast to the common convention of graphs in kinematic design [21], the nodes usually represent part elements while the edges embody their linkage in tolerance graphs [15]. In this context, Ballu and Mathieu introduced a graph-based approach for tolerancing of detailed design assemblies on the level of elementary surfaces extended by functional requirements, which enables a stringent tolerancing of geometry elements that directly affect the product's function [20]. Beside this, Giordano proposes different detail levels of graphs that enable the use of tolerance graphs from the conceptual to the detail design phase [22]. Moreover, Dantan et al. use graphs for visualization purposes in a data management model that supports the transition from a concept to a fully defined part by translating functional into geometrical requirements [5]. A more tangible implementation of the tolerance specification was achieved by integrating contact definitions and functional characteristics in the graph on geometry element level, which finally enables an automatic determination of MMC and LMC modifiers in joints [23].

In summary, the presented methods for the support of tolerancing activities in early design stages mainly focus on fully designed parts but do not consider design stages where geometry has not yet been fully defined.

3. Graph-based tolerancing in conceptual design stage

As it can be seen, though the consideration of tolerancing issues in early design stages bears great potential for time and cost savings in product development, there is a lack of methods supporting tolerancing activities in early design stages. As a response to this, a new approach to first tolerance evaluations in the conceptual design stage is developed. It is inspired by feature-based and graph-based methods [16, 23] and supports the tolerance specification as well as the evaluation of different product concepts in early design stages.

According to Fig. 2, the approach can be divided in several steps which are thoroughly described in section 4 and 5. First the product concept comprising the structure of relevant parts is visualized in a graph and is extended with interface relations between these parts. The resulting product structure graph does not contain detailed geometry information. To overcome this problem, the proposed approach uses semantic information with implicit design knowledge. This information is linked to *unified* terms for interface relations and parts and includes tolerance as well as engineering design knowledge. Together with the product structure, the generation of a tolerance structure graph with tolerances relevant for the fulfillment of product functionality is enabled. To ensure clarity and traceability, tolerance information that can be specified in conceptual design is visualized in this single graph.

However, the graph describes the tolerance structure of the whole product. Since designers ask for function-oriented tolerancing, a reduction of the graph facilitates the subsequent tolerance evaluation, which is detailed in section 5. For this purpose, functional tolerance chains relating to the previously defined functional requirements are extracted. These chains show the relevant geometry elements and corresponding tolerances affecting the function. Moreover, it enables the comparison of tolerance chains resulting from different product concepts and therefore facilitates the choice of robust concepts.

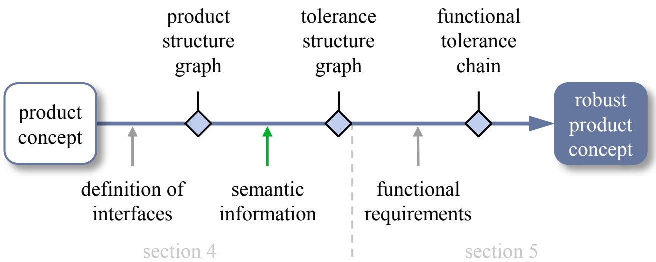

Fig. 2. Process of the presented approach to get robust product concepts

In the following, the proposed step-by-step method (Fig. 2) is applied to a case study of a hand-operated coinage machine to emphasize the practical relevance as well as the comprehensibility (see Fig. 3). Therein, the toggle lever transmits the hand movement into a stroke movement providing the necessary coinage force.

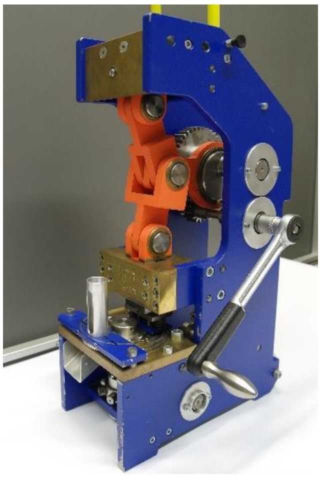

Fig. 3. A picture of the case study coinage machine

4. Generation of tolerance structure graphs based on the principle solution

The following chapter describes the transformation from a product concept or basic solution to a structured graph with relevant tolerances and geometry elements.

4.1. Generation of the product structure graph

Starting with the diagrammatic sketch (Fig. 4) or a structure chart, the structure of relevant parts and subassemblies necessary for the fulfillment of a product's functionality is already known at the end of the conceptual design stage [8]. Based on this information, the designer first creates a graph that shows the principle product layout (see Fig. 4). In this graph, each node represents a part or subassembly whereas the edges show the connections between them. Depending on the frequency of occurrence, standardized names are assigned to the nodes. Due to the fact that the product concept is limited to functionally relevant elements, the number of nodes and edges is typically low. Thus, the graph is comprehensible and its generation takes little time.

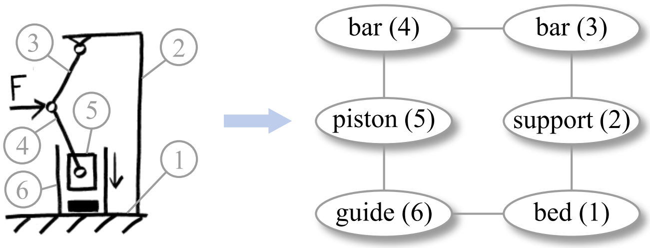

Fig. 4. Transformation of the diagrammatic sketch of a coinage machine into the corresponding product structure graph

In a second step, the designer defines the interface relations between the parts by naming the edges (see Fig. 5). Generally, the types of contact are limited to a few basic interface relations. This allows the use of unified relation names from a predefined list. Thus, the assignment of relations on part level is simple. Furthermore, the relation names are similar to the terms used for component placement in CAD-systems to enhance the usability in the design environment.

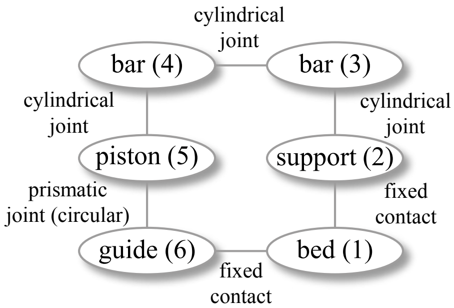

Fig. 5. Definition of unified interface relations for the completion of the product structure graph

4.2. Adding semantic information

The assignment of *unified* terms for parts and interface relations in the product structure graph (see section 4.1) allows adding semantic information, which widens the meaning of terms and supports the tolerancing process [18, 19]. In this contribution, the terms include tolerancing as well as engineering design knowledge and thus solve the difficulty of lacking geometry information for tolerancing in conceptual design stages.

As mentioned in section 4.1, unified terms for common parts with known relevant geometry elements or features can be used. However, that is only useful if no major design variation is expected during the subsequent design stages. Thus, it is mainly applicable for standardized parts like shafts and strongly depends on the industrial sector and the product variety. Motivated by knowledge-based engineering [24], the semantic information including geometry elements and their relations are linked to node names and are saved in a data base.

For example, it is common engineering knowledge that the piston (5) in the case study always consists of a piston skirt and a perpendicular piston crown. This information allows the automated expansion of the product structure graph (Fig. 5) by replacing the part node "piston (5)" with two geometry element nodes ("piston skirt (5b)" and "piston crown (5c)") and the associated perpendicularity tolerance in Fig. 6. Moreover, it is known, that the piston skirt is a cylindrical surface.

Fig. 6. Semantic information of the term "piston" for the extension of the product structure graph

The semantic information of standardized interface relations in Table 1 (limited to data relevant for the case study) enables a graph transition from part to geometry element level. It covers geometrical as well as function-oriented tolerancing knowledge about interface relations and supports designers by enabling the automation of the graph generation. The information about the corresponding degree of freedom for each joint type facilitates the choice of adequate interface relations and allows evaluating the resulting degree of freedom according to kinematic design [25]. The specification of geometry elements associated with the chosen type of contact enables the deduction of a geometry element graph. In doing so, the part nodes are replaced by nodes representing the involved geometry elements, similar to the procedure shown in Fig. 6. Moreover, recommended tolerances are added to the geometry element nodes (see Fig. 7).

Table 1. Semantic information for selected interface relations

interface relation	cylindrical joint	circular prismatic joint	fixed contact
degree of freedom	2	2	0
geometry elements	2 cylindrical surfaces	2 cylindrical surfaces	2 arbitrary surfaces
recommended tolerance	cylindricity	cylindricity	form or profile tolerance
functional requirement	rotational motion	translational motion	orientation of adjacent parts

However, the relative location and orientation of automatically generated geometry elements cannot be described with semantic information of interface relations. This would require the specification of tolerances between several parts, which is not supported by common tolerancing standards. Thus, the recommended tolerances are limited to those, which do not require a datum reference (see Fig. 7). Therefore, at this level of graph generation, tolerance specifications are only assigned to geometry elements themselves and are visualized by curved arrows starting and ending in the same node. For example, node 3b represents a cylindrical surface, which is the relevant geometry element in a cylindrical joint and is hence assigned with a cylindricity tolerance specification.

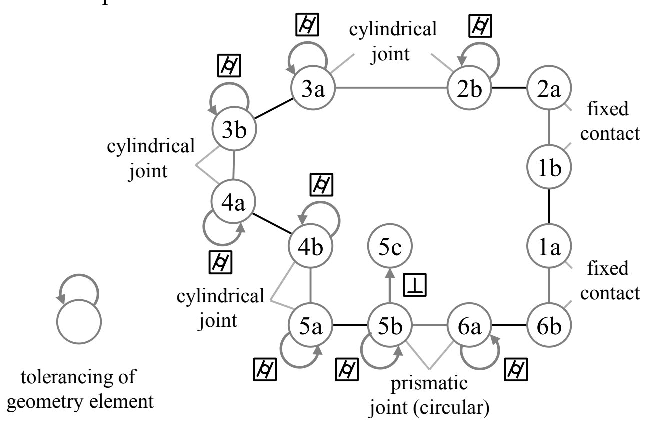

Fig. 7. Tolerance structure graph on geometry element level based on semantic information

Besides the automatic graph generation, this approach improves the traceability of tolerancing by adding functional requirements (see Table 1). This helps understanding the usefulness of recommended tolerances and further supports the assignment of particular tolerance values in the detail design stage. In addition, the type of geometry elements (e.g. cylinder, plane) dedicated to a node further improves the traceability of the automatic graph deduction (from Fig. 5 to Fig. 7).

The graph in Fig. 7 represents the product structure on geometry element level and the associated tolerances. It is solely based on the initial defined product structure graph (Fig. 5) and the semantic information. Therefore, the qualitative tolerancing is function-oriented and does not consider any other aspects such as manufacturing. Since these topics are hardly known in the conceptual design stage, it is justifiable to focus on functional requirements.

4.3. Extension of the tolerance structure graph

Because of the fact that the semantic information does not comprise each required tolerance, the graph needs to be extended. Thus, in a third step of the presented approach, the designer manually assigns additional tolerances. By doing so, the allowable location and orientation errors between geometry elements are specified and missing aspects may be considered.

As shown in Fig. 8, this process can be supported by predefined lists (grey framed boxes) based on semantic information. For example, the tolerances for geometry elements involved in fixed contacts are already limited to form or profile tolerances (see Table 1). The assignment of the type of geometry element corresponding to the node in the graph is another important information for predefining the tolerance symbol lists. It enables the reduction of available form or profile tolerances for the additional tolerancing of nodes or geometry elements. For instance, if a node represents a cylindrical surface, inadequate tolerances such as flatness are faded out.

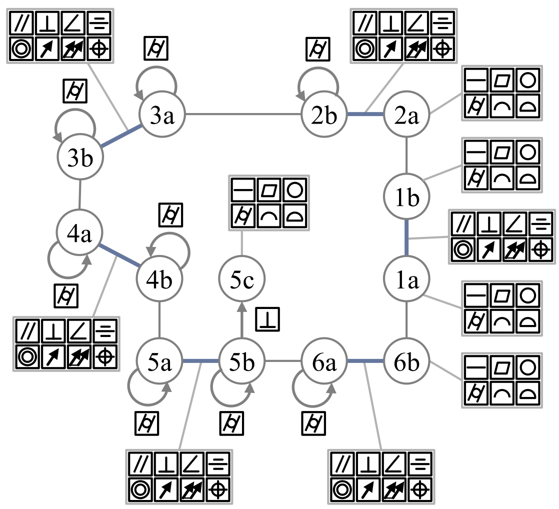

Fig. 8. Predefined lists for the manual assignment of additional tolerances

Besides the semantic information in Table 1, the systematic node labelling facilitates the tolerancing of edges in the graph. It allows defining relative orientation, runout and location of nearby geometry elements, which cannot be covered by the set of semantic information of interface relations (see section 4.2). According to the diagrammatic sketch (Fig. 4), the number within a node represents the corresponding part, whereas the letter indicates the geometry elements of a part. Because of the fact that tolerances are only applicable within a part, they can only be assigned to the blue edges between nodes with the same number in Fig. 8. Moreover, the datum references have to be defined.

The result of these steps is a graph including the structure of relevant geometry elements and the corresponding tolerance specifications (see Fig. 9). The mixture of undirected and directed graph is due to the different edges between and within parts. As the legend in Fig. 9 states, the directed edge for orientation tolerances starts from the datum reference node and points to the toleranced element. That clearly shows the relation between nearby geometry elements without the need for additional information signs that reduce the legibility of the graph. The form of visualization of derived geometry elements, such as axes, further reduces the complexity of graphs. Therefore, a single node represents the integral as well as the derived geometry element. It is visualized with a dashed circle around the node and can be used for tolerancing of the derived element such as the specification of the straightness of an axis. Furthermore, derived geometry elements are often the basis for the definition of orientation tolerances. For example according to the diagrammatic sketch in Fig. 4, the bar (3) comprises two cylindrical surfaces (3a and 3b). To guarantee functionality of the mechanism, the derived axes have to be parallel (see Fig. 9).

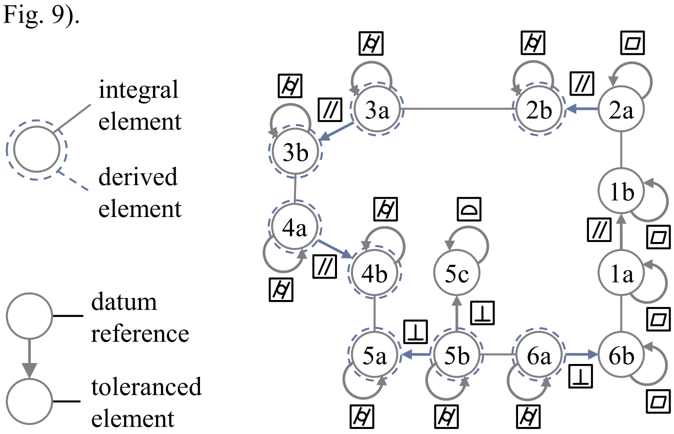

Fig. 9. Graph with relevant geometry elements and tolerance assignments

Summing up so far, the graph visualizes the qualitative tolerance specification according to the conceptual phase. However, dimensional tolerances as well as modifiers are not yet considered and need to be respected in detail design.

5. Evaluation of different concepts

Besides supporting the tolerance specification, the presented approach enables an early evaluation of product concepts regarding potential tolerance situations and thus facilitates the selection of robust product concepts. However, the graph such as in Fig. 9, considers the tolerance situation of an entire product. For a subsequent analysis, a simplification and reduction of the graph is necessary. Therefore, the definition of functional dimensions according to functional requirements is necessary to allow the identification and extraction of relevant tolerance chains.

For the presented coinage machine, the tilt between the stamp and the contact surface is the most important key characteristic for the coinage quality. Therefore, the graph in Fig. 9 is complemented with an additional edge between the involved nodes 5c and 1a. It leads to the generation of two closed tolerance loops within the graph and reveals that the functional dimension α is determined by two tolerance chains. This indicates a potentially over-constrained system. So, the designer is suggested to critically review the concept and check whether a redesign is necessary. According to the diagrammatic sketch in Fig. 10, the kinematics as well as the guide affect the orientation of the piston. However, the two tolerance loops are appropriate and necessary for the functionality. Therefore, the designer has to decide which loop is or shall be more restrictive. As suggested in Fig. 10, the tolerance chain, which includes the guide (6), is more restrictive and should be considered in the following. The required joint clearance in the second loop allows neglecting this loop during the subsequent tolerance evaluation. Therefore, the remaining graph in Fig. 10 comprises the relevant geometry elements and tolerances that affect the tilt angle.

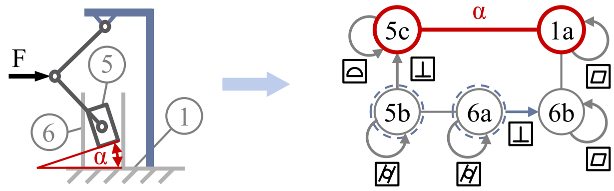

Fig. 10. Extracted functional tolerance chain of tilt angle

This approach enables the easy detection of relevant parts and tolerances and thus facilitates a first assessment of tolerance situation in conceptual design stage. This is in particular useful for large assemblies, where the relations between single geometry elements cannot be detected solely based on a diagrammatic sketch. Especially, the automated extraction of the tolerance chain allows the designer to get a quick impression of these relations. Moreover, the approach allows a straightforward comparison of different product concepts. In this context, alternative concepts lead to different tolerance structure graphs and resulting functional tolerance chains. The diagrammatic sketch in Fig. 11 shows a further concept for the coinage machine that only differs in the mounting of the guide (6). This leads to a tolerance chain that additionally comprises the support (2), see Fig. 11.

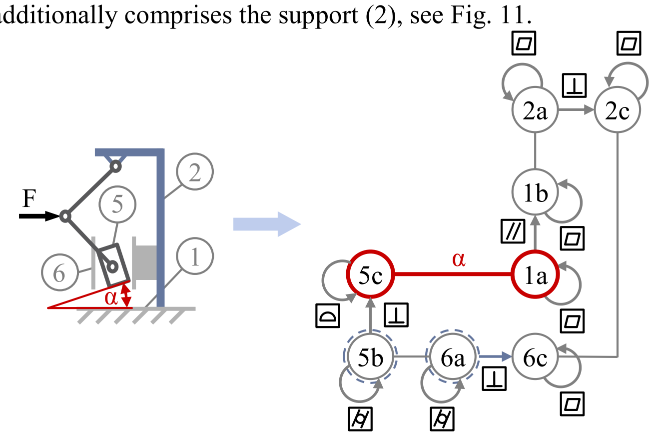

Fig. 11. Extracted tolerance chain of tilt angle for an alternative concept

Compared to the concept in Fig. 10, the functional tolerance chain for the tilt angle is significantly longer. The larger number of affecting geometry elements and tolerances impedes the assurance of the functional dimension α. According to Suh's axiomatic design [11], the length of resulting tolerance chain is a criterion for robust design. Therefore, the concept in

Fig. 10 can be considered as being more robust and should be preferred.

This graph-based evaluation of tolerance situations is applicable for each relevant functional dimension. Thus, it assists the designer in selecting robust product concepts to assure the fulfillment of functional requirements. Moreover, the approach reveals potential tolerancing problems that might occur in the subsequent detail design stage.

6. Conclusion and Outlook

It is widely acknowledged that the integration of robust design and tolerancing activities in early design stages holds great potentials for improving the product quality at low costs. Thus, an approach for tolerance evaluations in the conceptual design stage was developed. It is closely linked to the product development process and thereby guarantees high usability and acceptance in the design environment.

The proposed approach starts with a diagrammatic sketch of the product structure representing the product concept. Based thereon, a product structure graph is generated and stepwise enriched by implicit design knowledge and rule-based as well as manually entered tolerancing information. The resulting tolerance graph on geometry element level is then reduced to the tolerance chains according to the chosen functional dimensions. Therefore, it enables the straightforward assessment of concept robustness and facilitates the selection of appropriate concepts that reliably fulfill the functional requirements.

Moreover, the approach enables a concurrent product and tolerance design in the conceptual design stage, where the product's geometry has not yet been fully defined. Most of the necessary steps that cannot be automated are assigned to the product development process. Together with the use of semantic information, only little additional time is needed for the application of this approach. Starting from the diagrammatic sketch and using common terms for interface relations helps closing the gap between designer and tolerance manager. Especially the graphical visualization helps designers to understand the importance and the effects of tolerances on product's functionality. Thus, the designer becomes sensible for considering tolerances during the entire product development process, which finally leads to efficient and high quality products.

For further improvement of the usability, a thorough automation of the process is necessary. Especially the automatic extraction of tolerance chain graphs is a major challenge but would be useful for designers who are not entirely familiar with graph-based tolerancing. Moreover, the semantic information "degree of freedom" could additionally be used for quick evaluations of the resulting degree of freedom of parts and assemblies. According to the kinematic design, it would support the designer during concept development. Another yet unconsidered aspect is the effect of joint clearance.

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