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ORIGINAL ARTICLE

A tolerancing framework to support geometric specifications traceability

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Abstract Because manufacturing tools do not provide perfect geometry, designers have to control the deviations of the manufactured part's geometry. Nevertheless, the greater the number of toleranced parts in an assembly increases the more expensive the final product is. Consequently, designers only have to tolerance the influent surfaces of the mechanism that meet the functional requirement. Moreover, the earlier the geometric conditions are expressed in the design process, the better they conform to the functional requirements. In this paper, a product model is presented that allows designers to describe geometric specifications at any stage of the design cycle. In contrast to current models that support the functional and structural descriptions of the product, the product model presented also includes a description of the geometry with defects. Our product model used in geometric tolerancing enhances the traceability of the geometric conditions through the numerous transfer activities from conceptual to detail design. The benefits of the product model presented are illustrated with a car brake calliper design.

Keywords Geometric tolerancing · Traceability of geometric specifications · Product modelling

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1 Introduction

The aim of this paper is to present a data structure based on a product model to support geometric tolerancing expertise at any stage of the design process. The data structure presented has to support geometric specification description and to ensure the traceability of the geometric specification throughout the design process. Currently, geometric tolerancing expertise shares data with CAD modellers (Fig. 1). However, in a concurrent design context, a CAD-centred approach is satisfactory neither to start the geometric tolerancing expertise as long as the product geometry is not completely defined, nor to ensure the traceability of the geometric specifications. In contrast with current approaches based on CAD modellers, the presented framework is the common place where each expertise (CAD, manufacturing, geometric tolerancing) stores its own data [1]. In the approach presented, the CAD modeller is regarded as an expertise. CAD expertise provides geometric data on the product to the product model (Fig. 1).

2 Bibliography

The goal of tolerancing expertise is to control the defects of real geometry because the manufacturing process, the manufactured geometry (real geometry), is not equal to the nominal one. In geometric tolerancing, numerous studies have been carried out on geometric specification models.

2.1 Geometric specification models

Several geometric specification models aiming to describe the geometry with defects have been presented in the literature. Four main models are often used in tolerancing

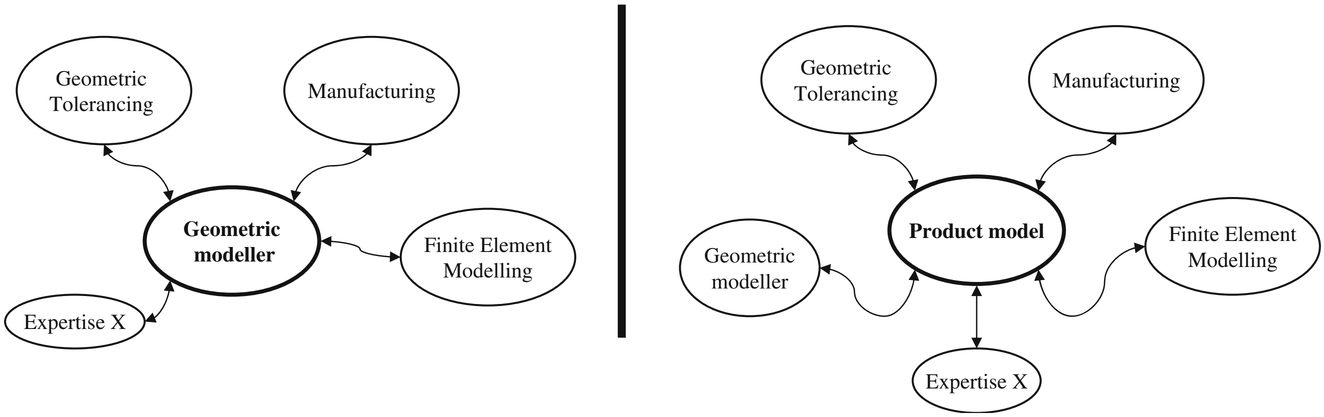

Fig. 1 Geometric modeller centred design versus product model-centred design

expertise: variational, envelope zone, structural, and a set of constraints models.

2.1.1 Variational model

In this approach, the geometry of the real part is described by variations of the nominal geometry. Each surface or geometric element of the real part is associated with a perfect shape element. In the variational approach, the variations between substituted elements can be described as follows:

- by vectors [2],
- by small displacement torsors [3, 4],
- by matrices [5–7],
- by metric tensors [8],
- by virtual gauges [9],
- by a finite set of constraints [10].

Two kinds of variations are described in this approach: the deviations between the substituted elements belonging to the same part, and the deviations between a couple of substituted elements belonging to two different parts in contact.

2.1.2 Envelope zone model

In the envelope zone approach, the real geometry has to lie in an envelope zone. This zone is obtained by offset of the nominal geometry [11]. The real geometry of a part is described as a set of tolerance zones. In a mechanism, each tolerance zone corresponding to the real geometry of a part is connected to others by constraints [10].

2.1.3 Structural model

In dimensioning and tolerancing, the often-used structural model presented in [12] is based on the TTRS (technologically and topologically related surface) theory.

With TTRS, a part is described by a tree of TTRS. This data structure is efficient in detail design, but it seems difficult to use in conceptual design for the product description that is based on functional requirements and a poor geometric description.

2.1.4 Set of constraints model

In the approaches presented in [13–15], the defects of the real geometry are described by a finite set of geometric constraints. 3D dimension-chain computation consists in Minkowski sums and intersection operations.

2.2 Geometric specification bibliography synthesis

Numerous specification models have been formalized in the case where the nominal geometry of a product is completely defined. Consequentially, the integration of the geometric specifications in the product description occurs at the end of the design process. The four main models presented in the previous paragraph contribute to defining the mathematical relations between a geometric condition on a given assembly and the geometric conditions on the parts of this assembly. These contributions allow simulating 3D dimension-chains with two approaches:

- the determination of the geometric conditions on parts of an assembly according to the respect of a known geometric condition on the assembly (tolerance synthesis).
- the determination of a geometric condition on an assembly according to the known geometric specifications on the parts of the assembly (tolerance analysis).

These two approaches allow considering a mathematical formulation according to the worst case or statistical methods (Monte Carlo, 6 Sigma) [16]. Nevertheless, the structuring of data manipulated by geometric specifications models in the design cycle is not generally taken into account.

2.3 Product modelling

Over the last 20 years, several studies have been carried out to represent a product during the design cycle. The product model is the logical accumulation of all relevant information concerning a given product during its life cycle [17]. Numerous approaches have been presented to allow a product description at any stage of the design process.

2.3.1 Functional and structural models

In [18] a product is described by three main entities: function, behavior and structure. The FBS model is suitable to describe a product in conceptual design before the geometry of the product is described. Several models have been presented in the literature to describe both functional and structural requirements of a product. Whatever the model, each representation of the product aims to enhance the geometric description of a product with functional information. In addition, these models assume that the concepts are sufficiently generic to be understood by each actor participating in the design process.

2.3.2 Product model dedicated to geometric modelling

In opposition to previous models, researchers proposed product models dedicated to geometric modelling:

[19] propose to describe a product from features. Features are information added to the geometric description of the product. Three types of features are defined: form features, precision features and material features. Form features define the nominal size and the shape of geometric entities. Precision features represent the acceptable deviations from the nominal geometry. Material features specify the type and the properties of the material.

[20] present a product model that integrates the geometric specifications according to ISO standards. This description allows one to describe size, form, orientation and location specifications.

[21] present a data structure dedicated to tolerance analysis during the design process from configuration to detail design.

2.4 Product modelling bibliography synthesis

Former studies on product modelling propose either functional and structural models or data structures dedicated to geometric modelling. The aim of this paper is to present a product model that ensures the traceability of the geometric specifications along the design cycle of a product. This paper focuses on the data structure manipulated by a specification model during the design cycle of a product. To allow designers to integrate geometric tolerancing earlier in the design process, we have to formalize the geometric tolerancing expertise. The geometric tolerancing expertise is made up of:

- a geometric condition transfer activity,
- data structuring integrated in a product model.

In order to compute 3D dimension-chains, the geometric condition transfer activity will characterize the manipulated data (inputs and outputs) according to a specification model. This will be discussed in paragraph 3. Data structuring aims to ensure the traceability of the tolerancing data induced by numerous transfer activities during the design cycle. This will be discussed in paragraph 4. In addition, an example will present a design scenario of a brake system in paragraph 5.

3 Formalization of the geometric condition transfer activity

Whatever the specification model, the geometric condition transfer activity consists of determining the geometric

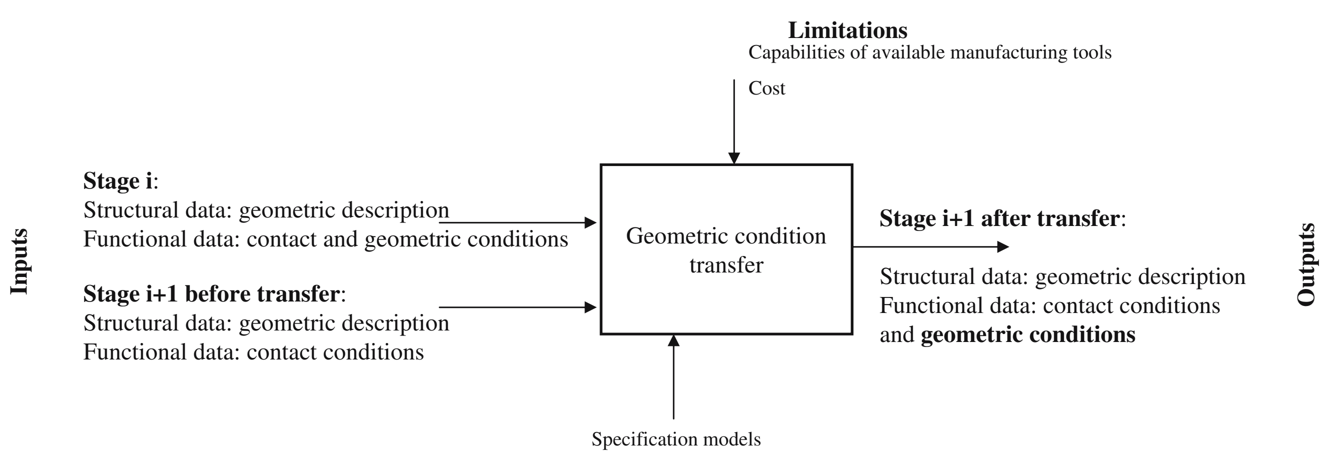

Fig. 2 Data manipulated by tolerancing expertise

conditions corresponding to stage i+1, from the geometric conditions of a product in stage i. As shown in [22, 23], the transfer activity can be described with an IDEF0 diagram. This representation allows describing the inputs, the outputs and the geometric specifications models available for the activity (Fig. 2). The inputs of the activity are composed of the product description in stage i and the product description in stage i+1 before transfer. The output represents the product description in stage i+1 after transfer.

3.1 Inputs of tolerancing expertise

The inputs of tolerancing expertise are both functional and structural data (see Fig. 2). In tolerancing expertise, functional data have to be understood as geometric conditions and contact conditions. Structural data correspond to the geometric description of the nominal geometry and the geometry with defects. The description of the geometry with defects is rarely taken into account in models dedicated to product modelling. The product description in stage i represents the structural data and the functional data (contact and geometric conditions) and the product description in stage i+1 represents the structural data of the product in comparison with the structural data in stage i. The functional data in stage i+1 before transfer include only the contact conditions.

3.2 Outputs of the tolerancing expertise

The product description in stage i+1 after transfer (see Fig. 2) includes:

- the product description in stage i+1 before transfer,
- the geometric condition (functional data) computed by the geometric condition transfer activity.

3.3 Limitations of the tolerancing expertise

The limitations of the tolerancing expertise can be the capabilities of the manufacturing tools available or the cost of the product due to the tolerancing schema. In a collaborative design process, the limitations of the tolerancing activity represent the link between the expertises that share the same data on the product (see Fig. 2).

3.4 Specification models

In geometric condition transfer activity, the specification models (Fig. 2) is one model among variational, envelope zone, structural and set of constraints models presented in Sect. 2.1. The specification model will allow computing the outputs but it will not influence the structure of data manipulated by the geometric condition transfer activity.

3.5 Geometric condition transfer illustration

The example used to illustrate the tolerancing expertise is the shaft of a car hydraulic pump (Fig. 3). In the example,

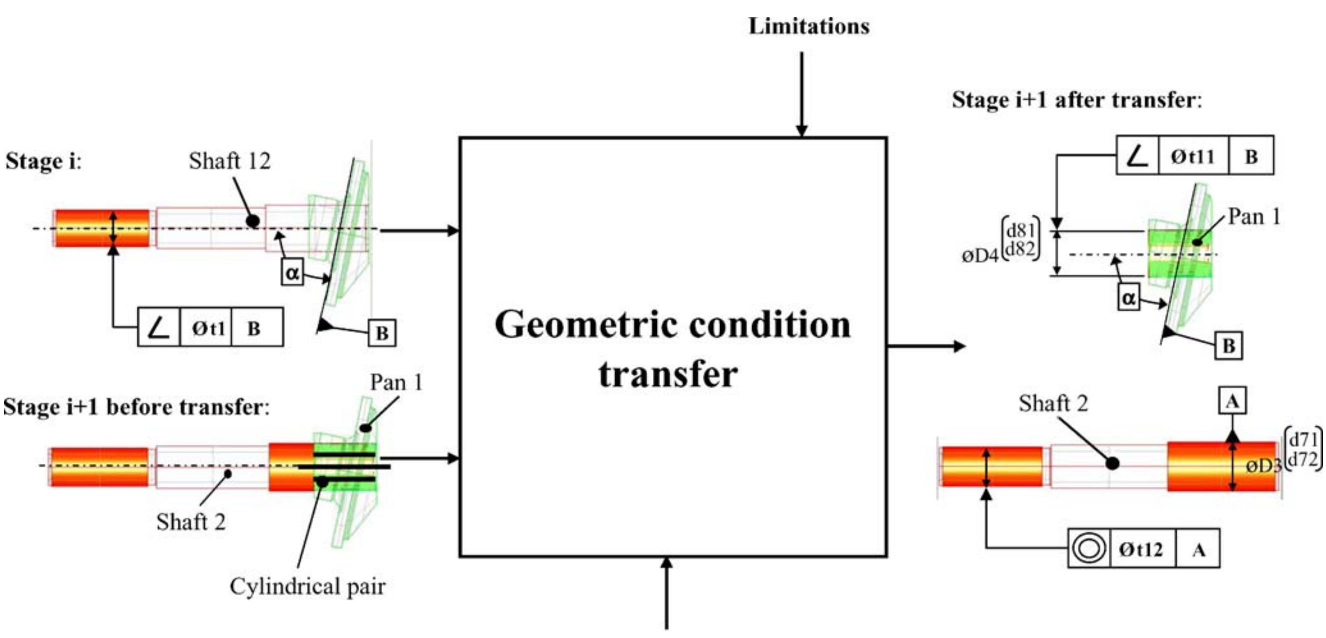

Fig. 3 Illustration of data manipulated by tolerancing expertise on a shaft of a car hydraulic pump

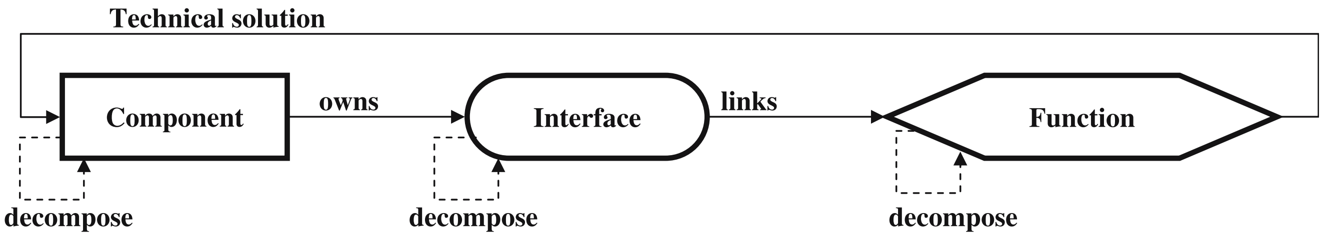

Fig. 4 Class diagram of IPPOP product model

stage i corresponds to a mechanism made with Shaft 12 and a geometric condition in order to control the angle between the plane surface and the cylindrical surface. At stage i+1 before transfer, the mechanism is divided into two parts Pan 1 and Shaft 2. This example corresponds to a structural decomposition (i.e., Shaft 12 divided into Pan 1 and Shaft 2) and a functional evolution by adding a cylindrical pair with interference fit (no degrees of freedom after assembly) between Pan 1 and Shaft 2 (see Fig. 3). This structural decomposition and the addition of a cylindrical pair represent the evolution of the product description from a stage i to a stage i+1. The tolerancing expertise consists of transferring the geometric conditions onto each part of the mechanism. The result of the transfer activity is a set of geometric specifications deduced from the evolution of the product between stage i and stage i+1. In the example presented, the geometric specifications that result from the transfer activity are described on Pan 1 and Shaft 2 (see Fig. 3). The result specifications (qualitative specifications) can be easily obtained for this simple example.

4 Integration of the tolerancing data in a product model

As presented above, the formalization of the tolerancing expertise allows determining which data are useful for this expertise. Moreover, the design process of a product involves numerous transfer activities. Thus, the result of a given transfer activity becomes the input of the following activity. To keep the link between the numerous transfer activities, we describe the tolerancing evolution of a product with the IPPOP product model.

4.1 IPPOP product model

To facilitate the work around the product in a collaborative context, in [24] we have described a product model based on three main concepts: component, interface and function (Fig. 4). These three entities allow describing both the functional and the structural decomposition of a product. Our contribution to the IPPOP project consisted of integrating tolerancing expertise in the product description [25, 26]. We assume that the IPPOP product model is well suited to support the description of each expertise. Moreover, this product model is a sub-set of a larger model resulting from the IPPOP project. The IPPOP project focuses on Integration of product, process and organisation for the enhancement of performance [27]. To facilitate the reading of the product graph representations which follow, each entity will be represented with a different shape, as shown in Fig. 4.

4.2 Correspondence between IPPOP entities and tolerancing data

In order to ensure the traceability of the geometric specifications from functional requirements to geometric specifications on parts, we have to split the tolerancing data into the product model entities. Starting from this statement, the correspondence between the IPPOP entities and the tolerancing data can be established.

4.2.1 Description of a component entity

A component describes the structural decomposition of the product in terms of assembly, sub-assembly, and part. To describe the full product structure, each component can be

Fig. 5 Instance of a component

CAD viewer representation	Component object attributes	Product model graph representation
	**Component** **Name**: Shaft 12 **Granularity**: Sub-Assembly **Geometry**: Nominal geometry	Shaft 12

decomposed into several ones. In the product model, the component Part 12 is described in Fig. 5. In the product model, a component is described by a set of attributes: the name of the component, the stage in the product decomposition process (granularity: assembly, sub-assembly or part), and the nominal geometry of the component. The definition of an IPPOP component can be exchanged with CAD modellers via STEP AP 203 [28]. Using the STEP resources of IPPOP product model, components in the product model can be automatically created when a designer opens a STEP file.

4.2.2 Description of an interface entity

The interface object allows describing the geometric elements of a component that are in relation with the external medium. In tolerancing expertise, an interface can be a surface, a line, or a point. An interface represents the simulated geometry substituted to the real geometry. For example, a substituted plane surface is described in the product model by a planar surface (perfect shape) with a different position and orientation from the nominal geometry. To describe an interface, a designer can pick (in the CAD viewer) a geometric element that corresponds to the substituted geometry of the interface in nominal position and orientation. The picked element allows determining several attributes: situation elements (plane, line or point), intrinsic characteristics (diameter of a cylinder or a sphere), and the limits of the interface (i.e., external wire of a planar surface or the two limit points on the axis of a cylinder, see Fig. 6). The type and number of attributes depend on the type of interface that has to be described. In Fig. 6, two instances of an interface object are presented to describe a cylindrical surface and a planar surface. These two interfaces are linked with the component Shaft 12 by the link between a component and an interface (Figs. 4, 6). This link signifies that the component Shaft 12 owns two interfaces Int 1 and Int 2. Nevertheless, attributes provided to describe an interface object allow to represent a spherical surface, a conical surface, etc.

A similar approach has been introduced in [29] to describe geometric elements.

4.2.3 Description of a function entity

Recent studies in TC 213 of ISO standards [29] propose a generic definition of the geometric specifications. In this approach, a geometric specification is a condition on a characteristic. A characteristic is:

- a location characteristic, the distance between two geometric elements,
- an orientation characteristic, the angle between two geometric elements,
- an intrinsic characteristic, the radius of a cylinder, the apex angle of a cone, etc.

The definition of a geometric specification presented in [29] is similar to the definition of a function in functional analysis, where a function is defined by a criterion, a level, and a flexibility. In this paper, this approach is used to describe both geometric specifications and functional requirements.

Hence, a function entity of the product model can represent a geometric condition, a contact condition or a

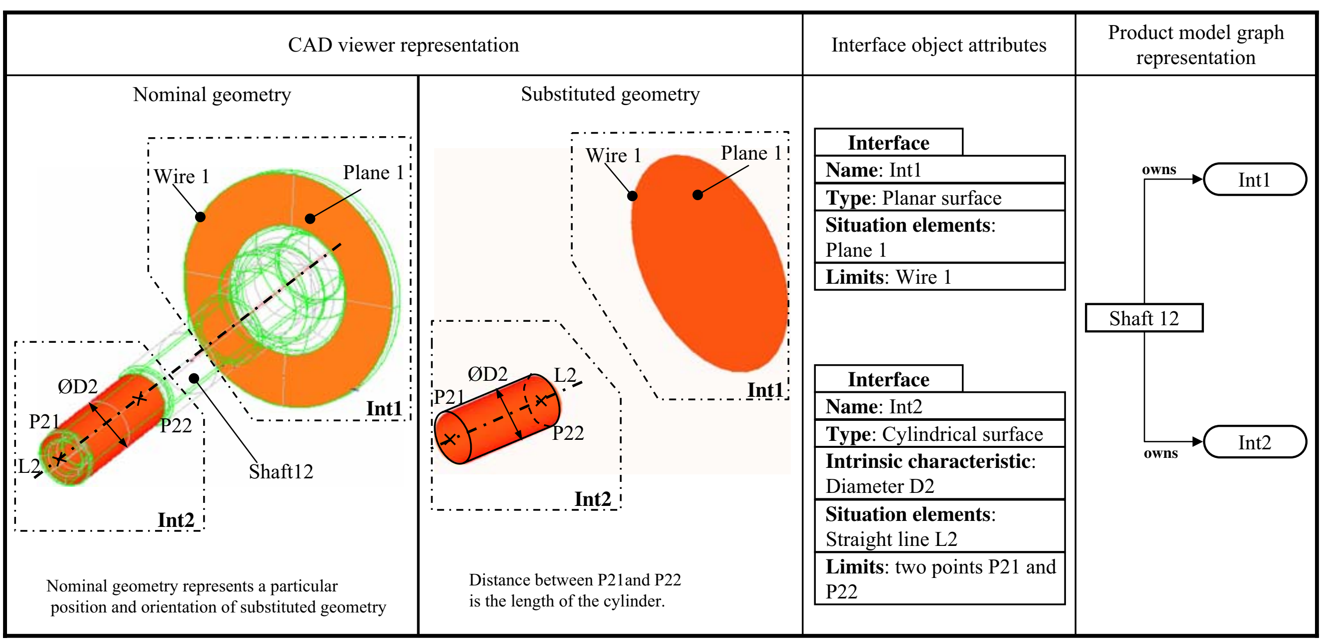

Fig. 6 Instances of interface

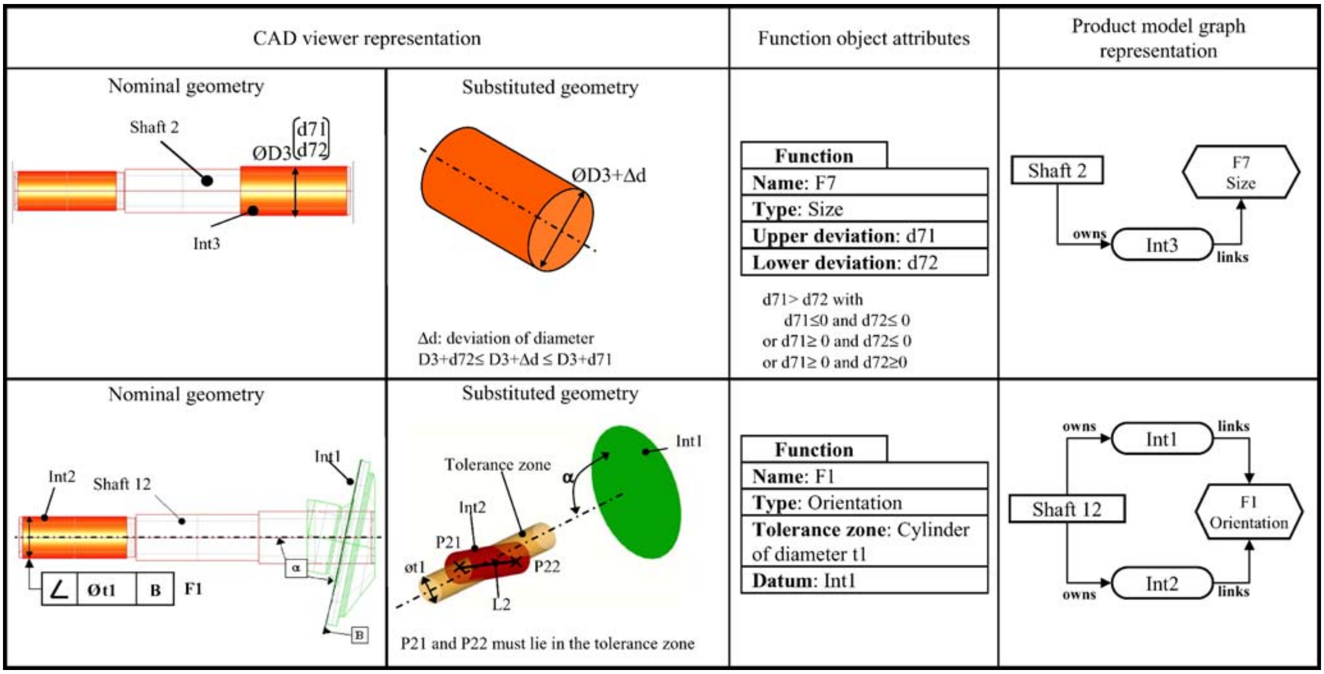

Fig. 7 Instances of function (geometric specifications)

geometric specification. The specifications supported by the product model are geometric specifications by tolerance zone, dimensional specifications (linear and angular) and roughness specifications according to [30–32]. In the product model, a set of attributes can be used to describe a specification. The type and number of attributes depend

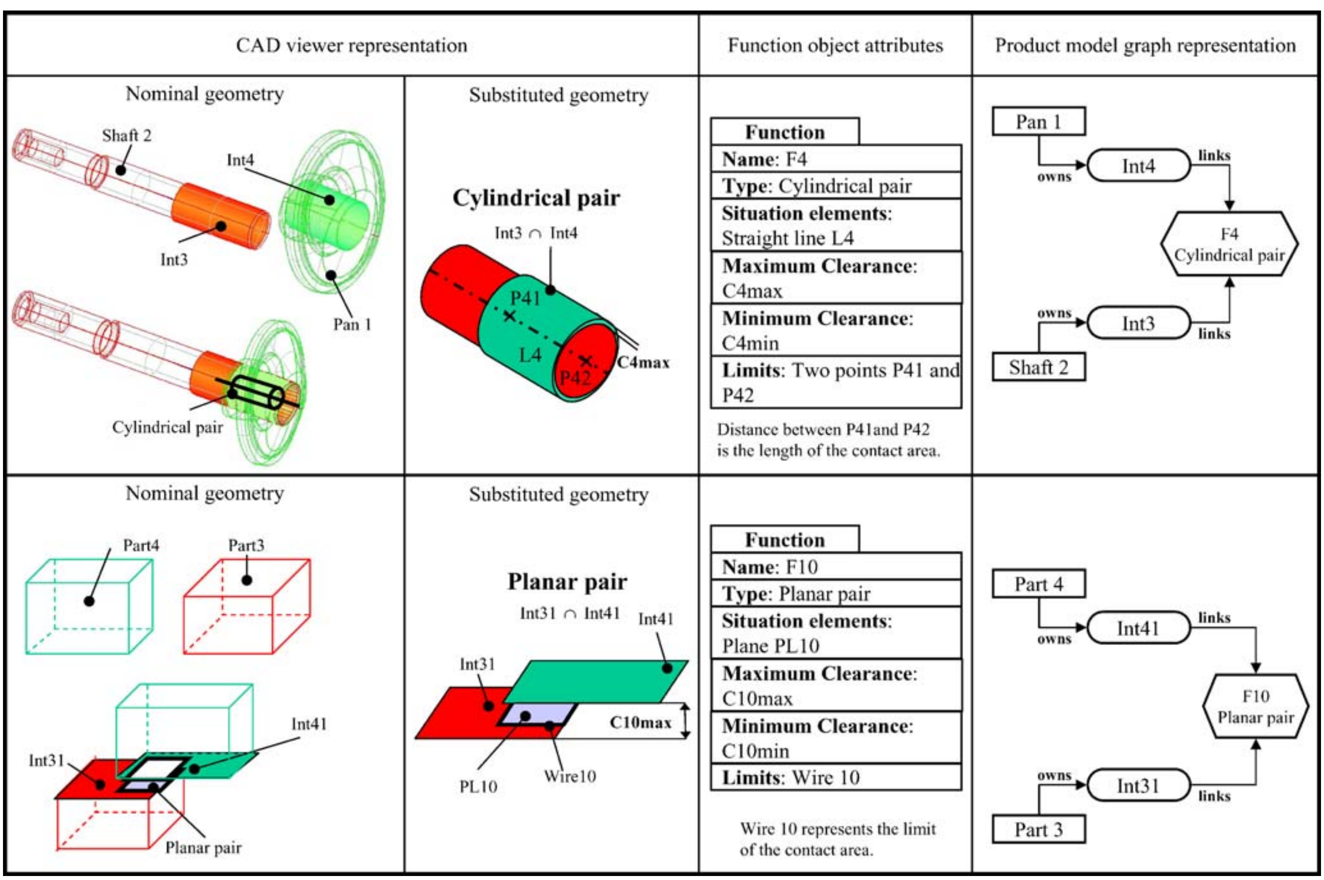

Fig. 8 Instances of function (contact specifications)

on the specification to describe and depend on the level of the product description. At the early stage of the design cycle, the specifications are described with few attributes and the designers enhance the specification description according to the evolution of the design cycle. In Fig. 7, two geometric specifications are described. Specification by dimension F7 can be represented by a function entity with an attribute corresponding to the type of the specification (size) and two attributes that represent the upper and the lower deviations. The characteristic ∅D3 pointed by specification F7 is not an attribute of the specification and is described as an attribute of the interface Int3 (see Fig. 7). A similar approach is used to represent a specification by tolerance zone. In this case, the function object owns an attribute that describes the type of the tolerance zone (a cylinder or two parallel planes), the dimension of the tolerance zone (diameter of the cylindrical tolerance or the distance between the two parallel planes) and datum. In Fig. 7, the semantic of the orientation specification (i.e. a condition on a characteristic) is that the axis of the simulated cylindrical surface must lie in the tolerance zone which is a cylinder of diameter t1. Moreover the angle between the axis of the tolerance zone and the datum plane is α degrees, and is calculated from the situation elements of Int 1 and Int2 in nominal position. In Fig. 8, a cylindrical pair and a planar pair are described with their attributes according to [33]. For example, the cylindrical pair represents the contact between two cylindrical surfaces (Int3 and Int4). The attribute named "limits" represents the two points (P31 and P32) that limit the contact area along L3 straight line (situation element of the cylindrical pair). Two attributes (C2max and C2min) represent the maximum and minimum clearance in the contact pair, respectively. These attributes allow describing both clearance fit, transition fit, and interference fit. We assume that C2max is always greater than C2min. In consequence, a interference fit is described with C2max≤0 and a clearance fit with C2min>0. In the case of a planar pair (Fig. 8), the value of C2min is always equal to zero because an interference has no physical sense for two planes in contact. For planar pair F10, the contact area is limited by Wire 10 on the situation plane PL10. In Figs. 7 and 8, the link between interfaces and a function is presented. This link signifies that a function links one or several interfaces according to the product model presented in Fig. 4.

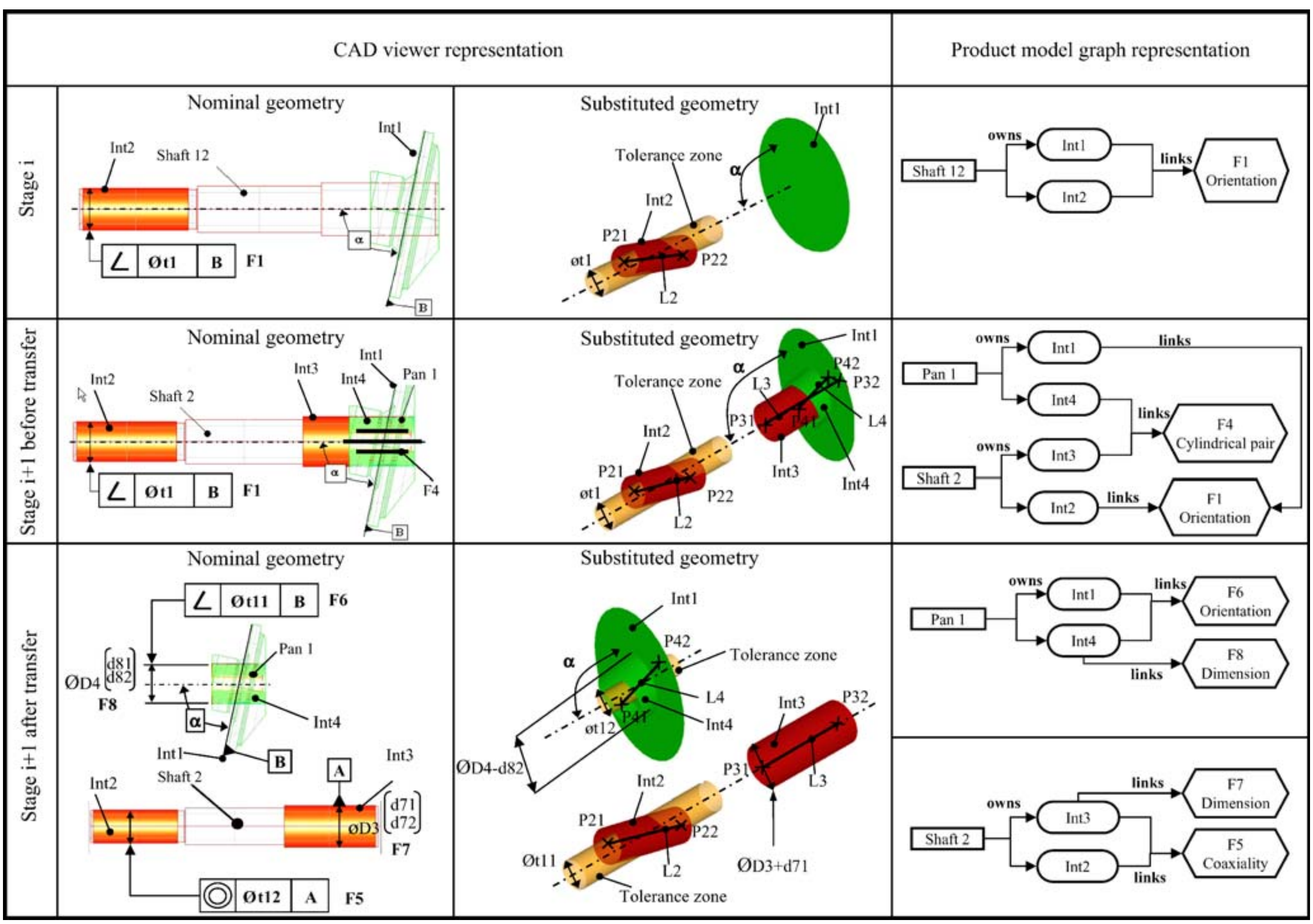

Fig. 9 Representation of data manipulated by tolerancing expertise on a shaft of a car hydraulic pump

4.2.4 Discussion of the decomposition links to ensure traceability

It is possible to model the data manipulated by the tolerancing expertise (inputs and outputs) presented in Fig. 2 with entities of the product model (component, interface, and function) presented in Fig. 4. Figure 9 illustrates how to model the data manipulated by the tolerancing expertise on the shaft of a car hydraulic pump introduced in Fig. 3 according to the representation of IPPOP product model entities (Figs. 5, 6, 7 and 8). Starting from the functional requirement F1 in stage i, we are able to describe the geometric specifications F6, F8 and F5, F7, respectively, on Pan 1 and Shaft 2 in stage i+1 after transfer. Nevertheless, it is impossible to detect in the data structure in stage i+1 after transfer (Fig. 9) that the geometric specifications (F5, F6, F7 and F8) are the result of the transfer of F1.

To answer to the traceability of the product evolutions, the product model allows one to decompose each entity (Fig. 4) into several ones. Figure 10 presents the decomposition link between components in stage i+1 before transfer. In this stage component Shaft 12 is decomposed into Pan 1 and Shaft 2. In stage i+1 after transfer, we illustrate the decomposition link between function entities. This decomposition link describes that functions F7 and F8 are the result of the transfer of F4 and that F5 and F6 correspond to the transfer of F1.

The decomposition link between function entities characterizes the geometric specification traceability. This link allows tracing the functional evolution of the product from geometric conditions on the product to geometric specifications on parts. Moreover, this link allows distinguishing the specifications that are the result of the transfer of a given condition among the specifications. The traceability of the geometric specifications presented in this example after a single transfer is detailed in the next paragraph in a design scenario.

5 Example

To illustrate the benefits of using the product model in terms of geometric specifications traceability, we describe the design cycle of a kart brake system. The design cycle represents three stages and two geometric condition transfers (Fig. 11).

The main function of the braking system is to realize a braking torque along the rotation axis of the brake disk. The

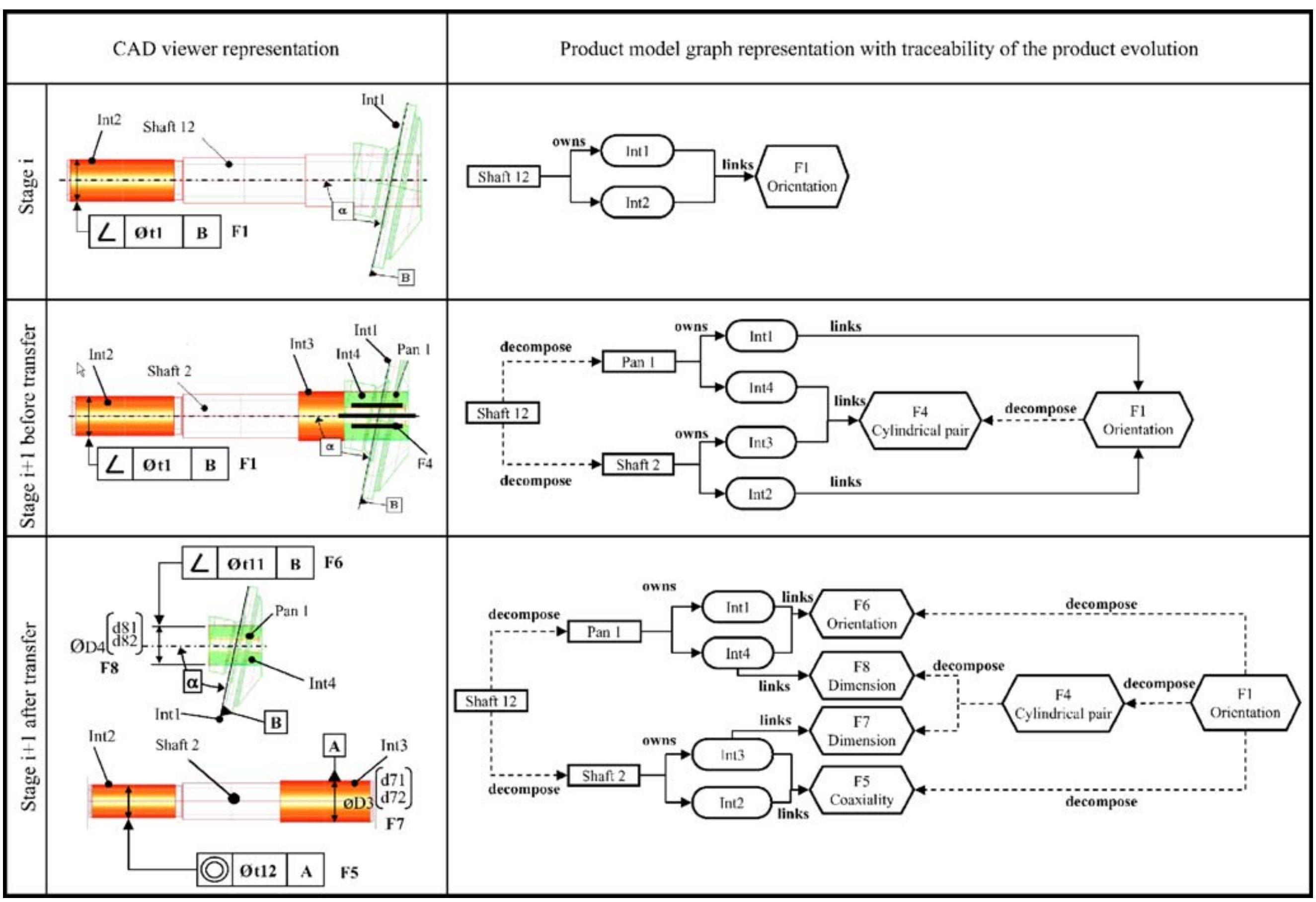

Fig. 10 Traceability of product evolutions

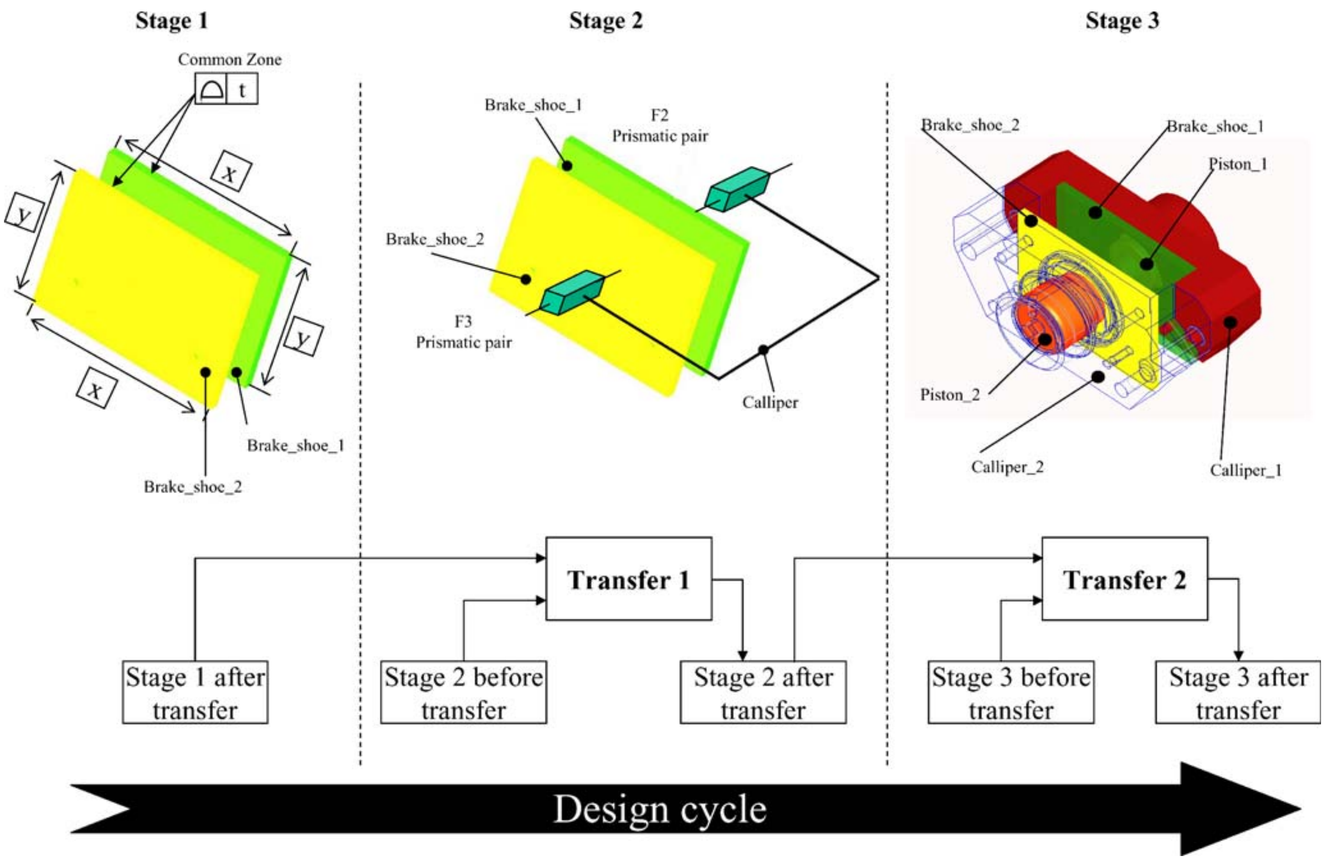

Fig. 11 Design scenario of a kart brake system

brake disk is not represented in Fig. 11. One criterion of this function is that the Brake shoe 1 and the Brake shoe 2 must apply on the brake disk two opposite forces along the same direction. This criterion is translated into the geometric condition F12, which ensures that the interface Int1 of the component Brake shoe 1 and the interface Int2 of the Brake Shoe 2 must lie in the same tolerance zone (Fig. 12). The tolerance zone is constructed by two offsets on the nominal interfaces Int1 and Int2. This first stage of the product design can be described with a CAD viewer representation and a product model graph representation as in paragraph 4 (see Fig. 12).

The result specification F9 (defined in stage 3 of the design scenario) of the transfer of condition F12 on part Calliper 2 is presented in Fig. 13 according to ISO standards. F9 represents a location specification between a

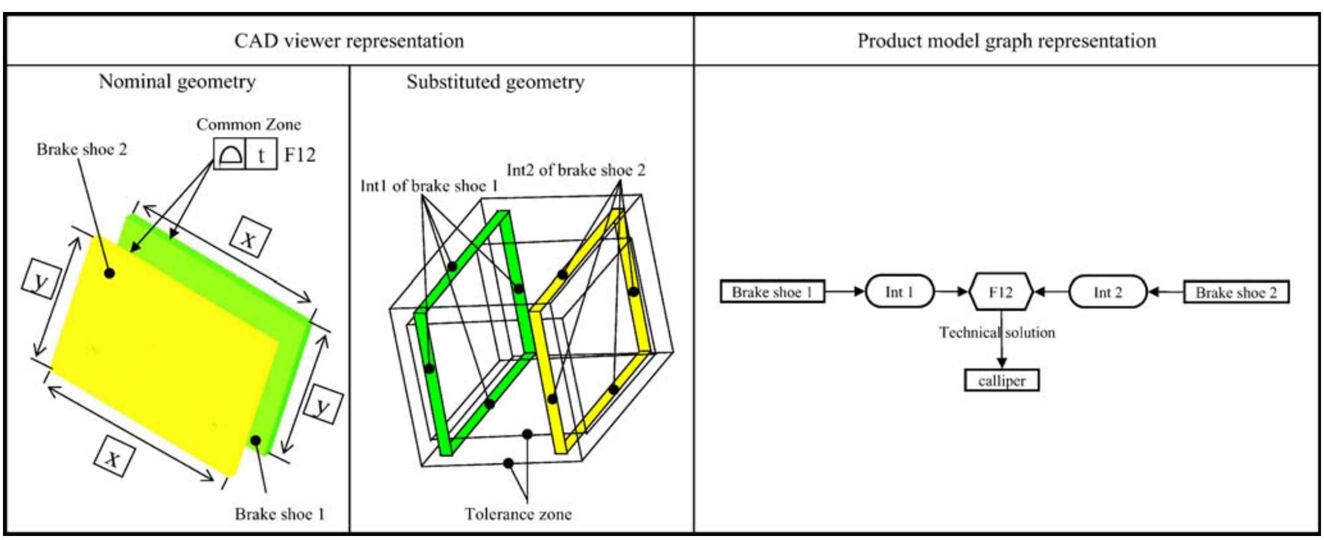

Fig. 12 Stage 1 of the design scenario

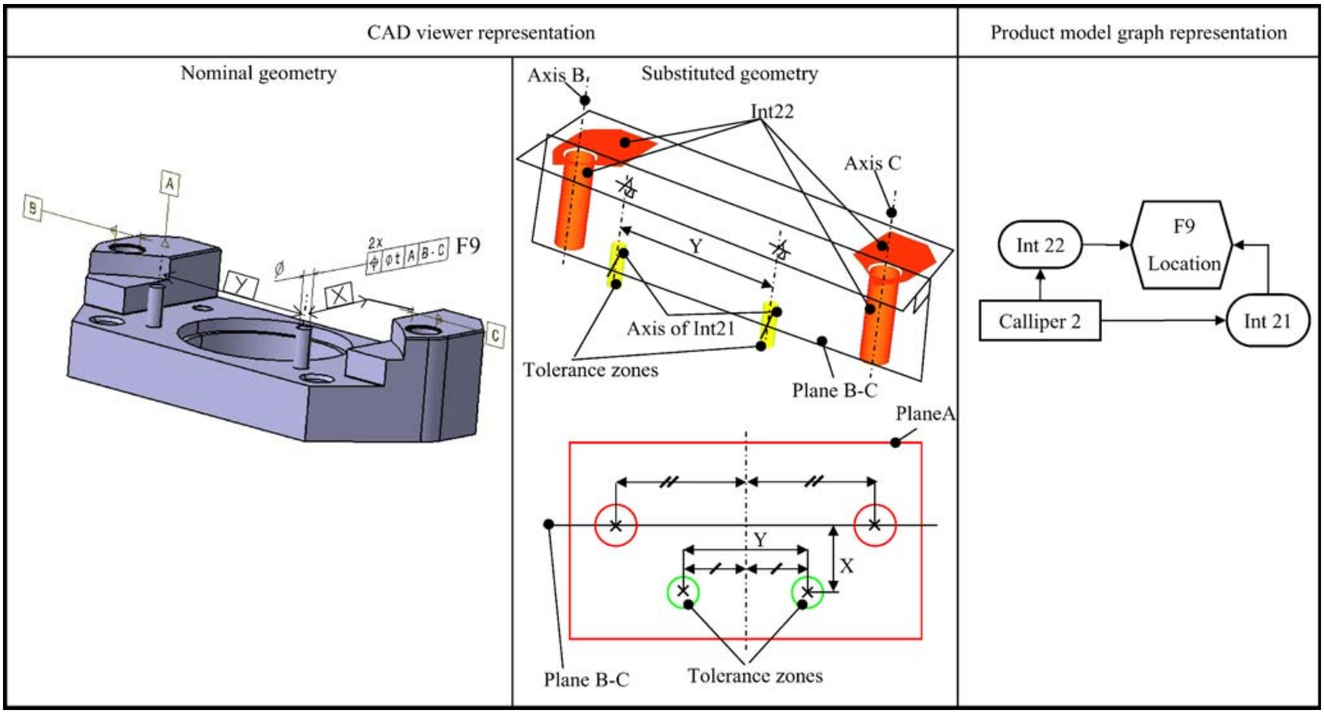

Fig. 13 Transfer result of F12 on Calliper 2

set of toleranced elements (Int 21) and a datum reference frame (Int 22). In this paragraph, we will show how the use of the presented product model can provide an answer to the traceability problem of the geometric specification from F12 (defined in stage 1) to F9 (defined in stage 3).

5.1 Stage 1 of the design scenario

Stage 1 of the design scenario consists in declaring the mechanism to design (Figs. 11, 12) using the links between entities of the product model. The link between a function entity and a component entity allows describing that the Calliper is a technical solution of function F12. In the product graph, three components are described according to the entity description presented in Sect. 4.2. The two brake shoes interfaces Int 1 and Int 2 are linked by function F12.

5.2 Stage 2 of the design scenario

The second stage of the design describes the kinematic of the mechanism (Figs. 11, 14). We assume that the pairs between the brake shoes and the calliper are made with the

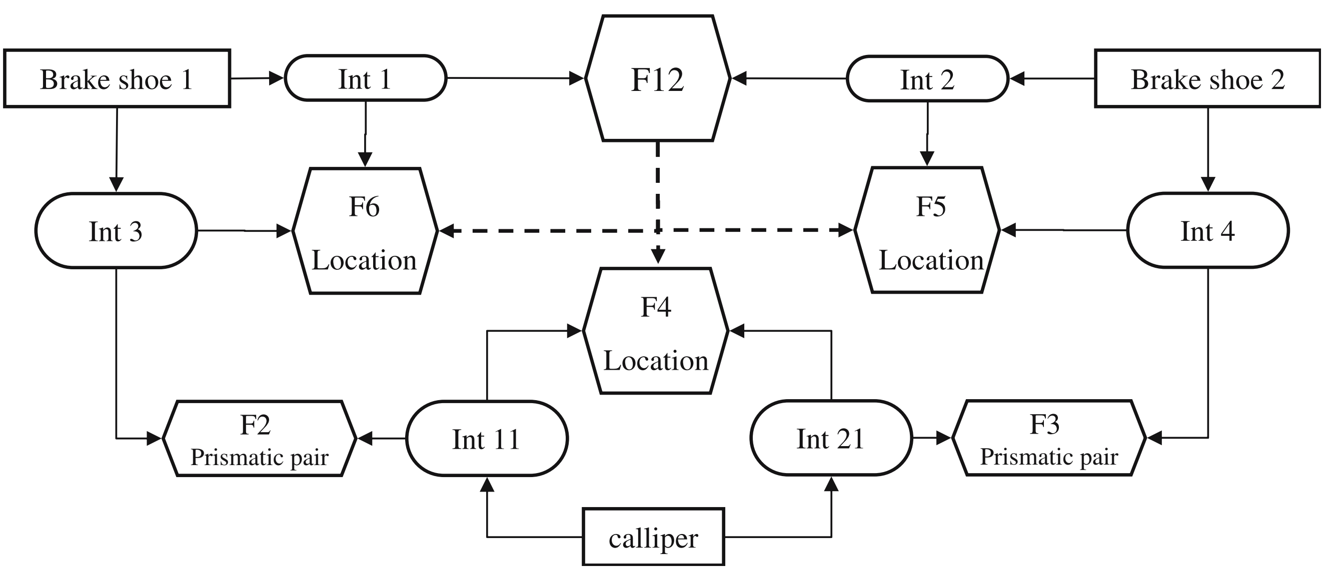

Fig. 14 Stage 2 of the design scenario

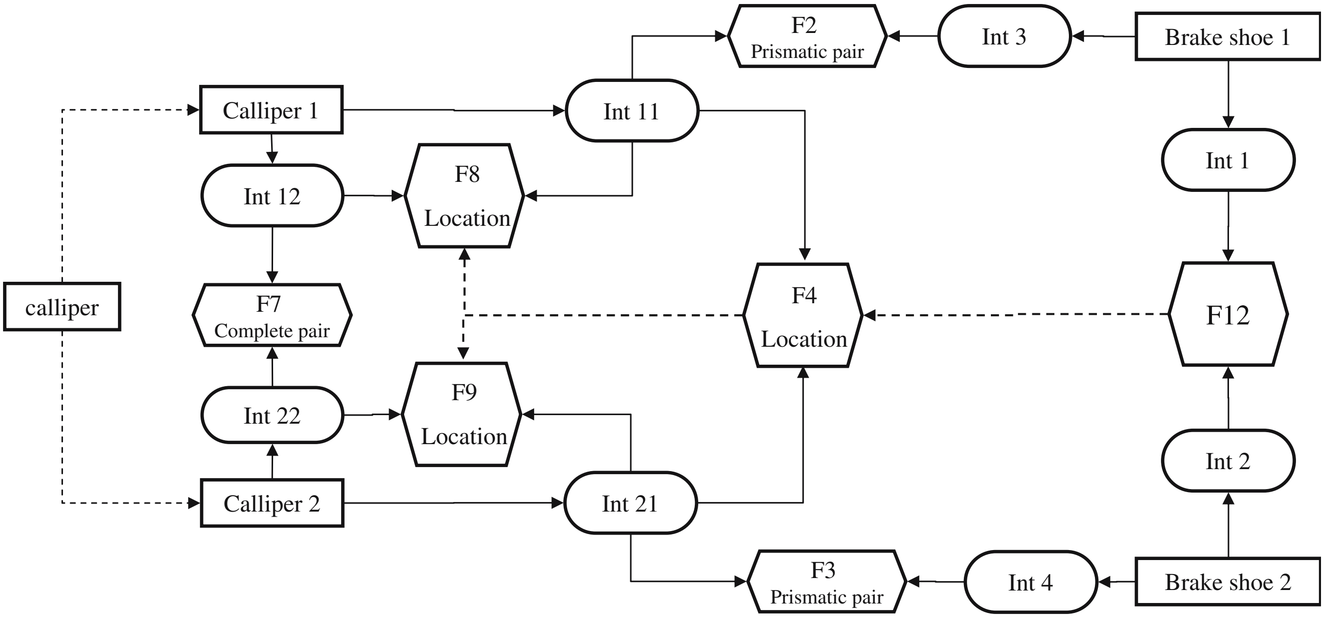

Fig. 15 Stage 3 of the design scenario

prismatic pairs F2 and F3. To represent the kinematic structure of the mechanism, the interfaces Int 3 and Int 4 are added on Brake shoe 1 and Brake shoe 2, respectively. Two interfaces Int 11 and Int 21 are added on the calliper. The prismatic pairs F2 and F3 respectively link the interfaces Int 3, Int 4 and Int 21, Int 11. At this stage of the design scenario, we do not know how the prismatic pairs are realised. As a consequence, the interfaces Int 11, Int 21, Int 3 and Int 4 are not geometrically defined. The interface entity in the product model allows one to represent a generic interface even if the geometry of this interface is not completely defined. As the kinematic of the mechanism is completely defined, we are able to transfer the geometric condition F12 onto the different parts of the mechanism. To ensure condition F12, the deviations between the influent surfaces have to be controlled. In this case, we only have to control the location (F4 specification) between the Int 11 and Int 21 of the calliper. Location F6 between Int 3 and Int 1 and location F5 between Int 4 and Int 2 are known data: they are introduced in the product model as a decomposition of F12 (Fig. 14).

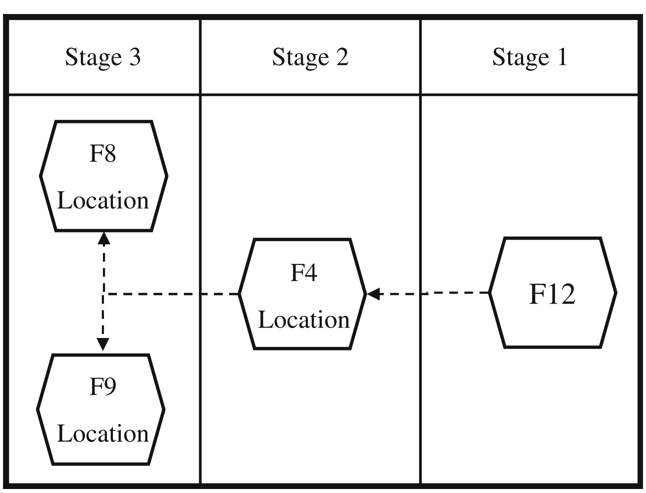

Fig. 16 Causality tree of geometric condition F12

5.3 Stage 3 of the design scenario

Stage 3 corresponds to the decomposition of the Calliper into Calliper 1 and Calliper 2 linked by a permanent pair F7. At this stage, we only have to determine which surfaces have an influence on location F4. As a result we obtain the conditions F8 and F9 that are a decomposition of F4 (Figs. 11, 15). An illustration of F9 using ISO standards is presented in the CAD viewer representation of Fig. 12. We suppose in Fig. 12 that the interfaces Int 21 and Int 22 are geometrically defined in the CAD viewer representation in order to give an illustration of F9 with ISO standards.

5.4 Traceability of the geometric specifications

The decomposition link of the function entity (Fig. 4) allows one to guarantee the traceability of the geometric conditions. In the data structure we are now able to search which specifications are induced by F12. We can browse the data structure through the decomposition links of function entity (Fig. 16) to find that in stage 3, the conditions F8 and F9 ensure the respect of condition F12.

The use of the presented product model ensures the traceability of the geometric specifications.

6 Conclusions

In this paper we aim to formalize the tolerancing expertise. The formalization of the geometric tolerancing expertise is rarely presented in the literature. Nevertheless, it is necessary to identify the inputs, the outputs, the needs and the limitations of the geometric tolerancing expertise. Starting from the description of the expertise, we can split the concepts used in tolerancing into the entities of a product model. Moreover, the presented product model based on three entities (component, interface, and function) and three links between these entities is a support for the geometric tolerancing description. The product model presented allows designers to describe nominal geometry (component entity), functional requirements on the product (function entity) and geometry with defects (interface entity). The last point is a benefit of the presented product model in comparison with product models described in the literature. The main benefit of the data structure presented is the traceability of the geometric specifications through the design process of a product. In the paper presented, we have illustrated the traceability from a function to geometric specifications. With IPPOP product model, designers are able to identify which specifications on a part ensure the respect of a functional condition described on a product at the first stage of the design cycle. In the example presented in this paper, the traceability of geometric specifications is shown through the transfer of a function with a single criterion but the IPPOP product model can also ensure the traceability of the geometric specifications from a multi-criterion function. Future works will concern the link between the IPPOP product model and commercial tolerancing tools where data described in the product model will be used to compute 3D dimension-chains or to write geometric specifications on a 3D CAD model. Therefore, the tolerancing expertise is not only used at the stage of detail design but can take place at the beginning of the design cycle even if the geometry of the product is not completely defined.

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