www.cadanda.com Computer-Aided Design AND APPLICATIONS

A Framework to Support 3D Explicit Modeling Education and Practice

Harald E. Otto[1] and Ferruccio Mandorli[2]

[1]Polytechnic University of Marche, h.e.otto@univpm.it
[2]Polytechnic University of Marche, f.mandorli@univpm.it

ABSTRACT

In this paper a framework based on the concept of functional dimensioning features is presented. It is aimed at supporting a methodological approach to explicit modeling with a focus on issues related to its use in MCAD education and practice. The proposed framework is based on the assumptions that shape, dimensions, and required manufacturing precision of a mechanical component are designed to fulfill specific functionalities. Principle formation and development regarding geometric entities and associated functional meaning are approached with an orientation on the concepts and definitions introduced by the GPS system of standards. Application of the GPS standards requires that dimensions and tolerances of the functional elements are specified within the nominal representation of a part or component. The traditional method of representing such information is a 2D technical drawing. However, explicit modeling provides new perspectives and opportunities for approaching 3D modeling, since it allows the addition of geometrical constraints and driving dimensions directly on the 3D model. In this context, the concept of functional dimensioning features is introduced, aimed at providing an integrative correspondence between concepts as specified by the GPS standards and the operative framework as provided by explicit modeling.

Keywords: CAD education, functional dimensioning, design intent, GPS standards.

1. INTRODUCTION

The recent widespread introduction of functionality and commands provided by commercially available CAD systems seems to signal the rise of a new approach to modeling in computer-aided design for mechanical engineering (MCAD). This new approach allows history-free modeling that is geometry-centered and which is referred to as *3D explicit modeling*, but also known as *direct modeling*. This modeling approach, sometimes also termed *variational direct modeling,* combines direct modeling with a constraint-based approach. It has been introduced with the aim of making editing and reuse of 3D models more intuitive, thus increasing ease of use and efficiency. Explicit modeling is not just a different approach to CAD model editing. Rather, it represents a modeling paradigm in itself. In contrast to traditional feature-based modeling, explicit modeling considers the entire shape of a model at each stage of the modeling process, without reference to the sequence of previously executed operations. Hence, explicit modeling is history independent so that the order of modeling operations used to create a model does not directly impact the way a model can be altered. In this context, explicit modeling technology provides an opportunity to reconsider the way a designer can be supported by the use of a 3D modeling system. In particular, this modeling paradigm introduces a different perspective on how the design intent can be captured and represented. The first challenge here lies in the methodology employed by users to define design intent. However, a second challenge is to produce a MCAD system which can recognize design intent in any form of geometry and its defining parameters and then compile it into a consistent set of geometric constraints.

Design intent preservation is a well-known issue in the MCAD domain [18,20]. Creation of 3D models that are capable of capturing and preserving the design intent is important from several viewpoints [13]. It is necessary to communicate the functional meaning of a component and to make model adjustments without modifying, or even perhaps destroying, geometric entities related to functional requirements. It is in this context that motivation has arisen for work on a methodological approach, where design intent in the form of semantics related to component shape can be specified and preserved using explicit modeling

Taylor & Francis
Taylor & Francis Group

technology. This endeavor requires first of all the development of a framework where traditional engineering concepts will find the appropriate conceptual and practical correspondence with framework entities and modeling system functionalities. The objective of the work presented in this paper is to develop such a framework based on the concept of functional dimensioning features. This will support a methodological approach to explicit modeling with a focus on issues related to its use in MCAD education and practice. In this context, particular preference is given to the definition of methodologies aimed at preserving the design intent while at the same time maintaining best practice, and with its main interest on the teaching of strategic knowledge.

The paper is structured as follows. In section 2 some background information is presented, together with an outline of scope and objectives. This is followed by discussions on functional dimensioning and the Geometric Product Specification Standards (GPS), and the introduction of a novel framework and its central concepts in section 3. Insight on the framework translation, together with application examples related to the context of MCAD education and practice, are given in section 4. Finally, in section 5 a summary with conclusions and the outlook for future work is presented.

2. BACKGROUND, SCOPE AND OBJECTIVES

2.1. Current MCAD Technology and Modeling Practice

In the last two decades development of MCAD systems has mostly been oriented towards the feature-based modeling paradigm. This is a trend that is also reflected in the modeling functionality and data structures provided by the majority of current commercially available MCAD systems. The concept of form-features, coupled with parametric functionality and feature history trees, has been the foundation for enhancing CAD systems. Based on that foundation, efforts in both academia and industry took decades to drive developments from pure geometric modeling systems, which were based on the instantiation of geometric primitives and Boolean operations, to integrated and more efficient design support systems. An overview on those developments from the early 1980s to the mid 1990s can be found in [17,21], while recent developments with an enlarged focus are now also able to consider feature technology related aspects across various phases of the product life cycle, and are described, for example, in [2,14,16,19].

Within this context, features were meant to be the concept capable of capturing the design intent (see also discussions in [1,13,18,20]), while parametric functionality was supposed to provide a means for making model alteration and reuse easier. Here it cannot be denied that the introduction of the feature-based approach for system development contributed to a considerable improvement in the efficiency of MCAD systems, resulting in a push to significantly speed up the 3D modeling process. However, one needs to consider the way MCAD systems are used in current commercial and industrial design practice. When a CAD model change is required, it is standard practice to re-make the model from scratch instead of modifying an existing model. This is obviously an unfortunate custom that was neither intended nor anticipated. This relates directly to our inability to translate the promising potential of feature technology into practice through coordinated development of MCAD systems, models, and data exchange standards that can be implemented in a manner consistent with the basic concepts and functionality of a true feature-based approach.

The reasons for this inability are manifold, complex, and interrelated, and therefore cannot be assumed to be purely of a technological nature. Two currently prevailing conditions from industrial practice directly reflect on this situation. On the one hand, there is an increasing need to exchange CAD models between different systems. This need is increasing, due to globalization driven outsourcing and distributed design teams, but in most cases these forces merely result in a loss of feature technology related structures such as the feature tree. As an immediate consequence, a 3D model is created during the transformation process which is pure three-dimensional geometry free of any modeling history and deprived of any design knowledge and intent. This is therefore often referred to as *dumb geometry*. On the other hand, feature-based CAD models tend to rapidly lose the engineering meaning which is encapsulated in design intent, if they are re-interpreted by experts different from the original model creators. These new interpreters may be members of another design team, or even experts from another engineering field, such as manufacturing. Assuming that issues arising from the first condition can mainly be attributed to technological problems, which could be overcome eventually, issues from within the second condition are obviously not of a purely technological nature, but rather interrelated with design process interpretations and associated concepts, arising from entirely different viewpoints. This in turn relates to one of the disputed tenets central to the feature modeling approach, which assumes that a form feature represents *the* functional meaning of a shape, instead of representing just *one* among several possibilities. For example, during the design of a part or component, the required basic functions do not differ much, if at all, but a change in the shape is likely to occur, especially during re-design. A request to change some dimensions of a feature-based system can be achieved in a straightforward and efficient way by modifying the dimension parameters of features present in the CAD model. However, a request to change the shape of a feature, for example from a prismatic pocket into a cylindrical pocket, proves to be quite a challenging task. Conceptual limitations of the feature-based approach, combined with a weak and sometimes unsystematic methodological approach on the part of users, can and will easily result in a complex counter-intuitive modeling history and feature trees which make model alteration almost impossible in today's highly competitive and resource limited industrial practice.

Recently, MCAD system developers have begun to address some of these issues through efforts in two completely separate directions. Firstly, they have extended the set of feature-based commands to include local modification commands that can be used, for example, to move, rotate or cut single surfaces of the feature-based CAD model. Secondly, they have introduced a new modeling approach, referred to as either *explicit modeling* or *direct modeling*. The explicit/direct modeling approach is based on the definition of 2D regions the user can interactively push, pull or twist, to add or remove volume to the model shape. Here a region can be an entire model face or a bounded area defined by a sketch on a plane. Geometric constraints between model entities as well as shape dimensions are directly linked to the 3D model and they determine (drive) the way the model can be altered. However, in contrast to the feature-based approach, explicit modeling considers the model shape as a whole at each stage of the modeling process, without any reference to the sequence of previously executed operations. Hence, explicit modeling is history independent, meaning that the order of modeling operations used to create a model does not directly impact the way a model can be altered. Considering the way a CAD model can be altered, in terms of both dimensions and shape, we can discern appreciable benefits of the explicit/direct modeling approach over the feature-based modeling approach. However, further investigation is required to gain insight into and better understanding of the interacting elements involved and the impact of this new modeling paradigm in respect to issues of dumb geometry and the preservation of design intent within CAD model exchange and re-modeling.

2.2. Explicit Modeling Characteristics and Emerging New Opportunities

From a technical point of view, direct/explicit modeling is supported by an extension of the variational approach (cf. [6,15]) from 2D to 3D. However, interpreted from a more theoretical point of view, it relates to actions performed by the user, to directly add or remove driving dimensions and geometric constraints on the 3D geometry. Here the latter are converted into a mathematical system of equations that an algorithm has to solve to find a sound and consistent configuration of constraints. As variational technology easily leads to either over-constrained or under-constrained systems, there is a high risk of producing models within the context of 3D modeling which are either locked (no consistent modification possible under given constraints) or of unexpected geometry. In order to limit this risk, users should adopt a systematic and coherent modeling approach paying attention to dimensions and constraints that are finalized for the preservation of the design intent, as those will also preserve the function related to the model shape should model alteration be required. One way to achieve this goal is the careful use of 3D dimensions and constraints, as is usual in the field of technical product documentation. In this context, the traditional means used to transfer a solution from design to manufacturing is technical drawings. The technical drawing of a part or component must contain the information necessary to facilitate a univocal interpretation of the depicted shape, which includes all dimensions and tolerances required for manufacturing. In this sense, the technical drawing is a graphical language, which is based on commonly accepted rules and criteria, most of which are now specified by international standards.

Functional dimensioning represents one out of several methods provided by the standards for determining dimensions and tolerances to be added on technical drawings. The tenet central to this method is to unambiguously specify the functional meaning of the geometric elements that compose the shape of a part or component. In this context, the direct/explicit modeling paradigm supports a more intuitive way to manage the model during the design process, by making it easier to iteratively refine CAD models from a roughly defined geometry into a final detailed geometry. Additionally, this modeling paradigm provides a new perspective for 3D modeling by facilitating functionality to globally add or remove dimensions and geometric constraints to/from the shape of the model at any time during the modeling process. This allows for the direct application of functional dimensioning criteria while modeling in 3D. In such a scenario, the application of functional dimensioning criteria within direct/explicit modeling enables the unfolding of interrelated benefits, as characteristics intrinsic to functional dimensioning will result in a fully constrained 3D model, which in turn, when associated with functional dimensions, will be able to communicate the design intent. However, an overall framework is required in order to translate those benefits into education and practice. The framework needs to be able to integrate concepts and structures central to the explicit representation of derived nominal elements as introduced by the GPS standards for dimensioning and tolerancing. It must also accept the use of such elements as elements of reference for dimensioning, and it must be able to distinguish between functional and non-functional dimensions. This requires the implementation of improvements both in methods employing the direct/explicit modeling approach and in the functionality provided by future MCAD systems. It is in this context that we wish to introduce our proposed framework, based on the concept of functional dimensioning features. The framework is aimed at supporting a methodological approach to explicit modeling, with a focus on issues related to its use in MCAD education and practice.

At this point, it should be noted again that the idea of explicitly adding manufacturing information like dimensions and dimensional and geometric tolerances to 3D models, in order to facilitate manufacturing planning, dates back to the mid 1990s and to the work of Clément [4]. More recent works have also highlighted how manufacturing information, if directly related to the CAD model, could facilitate the definition of a more coherent tolerancing process [3], as well as supporting the control procedures [5]. Recently, the majority of MCAD systems developers have included functionalities aimed at conveying non-geometric attributes in 3D CAD and collaborative product development systems necessary for manufacturing product components or sub-systems. Such annotations and their functionalities are nowadays referred to as *product and manufacturing information* (PMI). The PMI may include plain text, geometric dimensioning and tolerances, surface finishing, and material specifications. The PMI (annotations) are created on the 3D CAD model, associated with edges and faces, and can then be exported by means of neutral formats, to be visualized within collaborative product development systems, nowadays available even on mobile devices such as tablet computers and smartphones.

Although some 3D model formats enable computer-aided manufacturing software to directly access PMI data (to be used for CNC programming or even tolerance analysis performed by means of CMM machines), PMI, as intended up to now, consists only of "static" information, such as labels related to the 3D CAD model, without any functionality to enable a model shape change as a result of a PMI definition change. In other words, PMI dimensions are driven dimensions and not driving dimensions, as they do not play an active role in the process of altering the model shape.

Within this context, the above mentioned functionalities, introduced by the direct modeling approach, provide a completely new scenario and offer new opportunities. Some of the traditional PMI information (namely the dimension information), can now become "dynamic" information due to the fact that it can be represented by the 3D driving dimensions that the direct modeling approach allows us to add to the 3D global shape of the model. This new opportunity to overlap the concepts of PMI dimensions and driving dimensions makes it evident that significant process information (a PMI dimension) can also be actively involved in the model alteration process (as a driving dimension), or vice-versa that a dynamic dimension can be used to represent process relevant information.

3. APPROACH, CONCEPTS AND FRAMEWORK

3.1. Directions of Concept and Structure Formation

The design and development of the framework are aimed at relating principles and concepts defined by the GPS standards to functionalities provided by explicit modeling systems, in order to make explicit the semantics designers associate with a model shape. In order to reach this goal, the concept of functional dimensioning features will now be introduced. This novel framework is based on several assumptions as follows. The shape of a mechanical component is designed to fulfill elementary functionalities such as beat, shoulder, alignment, guide, stiffening, and fit. The geometric elements related to elementary functions are the most critical, and therefore they are directly related to explicit dimensions and tolerance information. International standards exist (GPS and related standards) that define basic concepts and principles appropriate for the specification of dimensions and tolerances.

To successfully approach framework development using this new modeling paradigm within the context as outlined above, an application-independent, systematic viewpoint on the relationship between engineering function and geometric entities has been used, which is suitable for both education and industrial practice. In order to direct principle formation and development in relation to geometric entities and associated functional meaning, we propose to make reference to the concepts and definitions introduced by the GPS system of standards (cf. [10]). The aim of the GPS system of standards is to provide a consistent framework for the univocal specification and interpretation of geometric products, while supporting the definition of unambiguous measuring procedures. These definitions are not yet completed for all parts. In the field of mechanical engineering, this is the fundamental premise to preserve the design intent from the ideal domain of design to the physical domain of the manufactured component. This is meant to ensure both that the manufactured component will be able to provide the elementary functions as specified by the designer in the mechanical engineering drawing and that there will be part interchangeability.

Application of the GPS standards requires that dimensions and tolerances of the functional elements are specified within the nominal representation of the component, i.e. the representation of the design solution. On the other hand, the explicit modeling approach allows the user to add geometrical constraints and dimensions directly to geometric elements, independently from the modeling sequence that leads to the model shape. It is in this context that we shall introduce the concept of a functional dimensioning feature (FDF). The composition, structure, and semantics of the geometry and spatial properties of FDF are derived from principles and concepts used in geometric modeling. Such a structure allows for the employment of functional dimensioning features as a means of integrating definitions and concepts such as features of size, situation features, and intrinsic characteristics, stemming from the GPS standards and being central to functional dimensioning with the functionalities as provided by an explicit modeling system.

3.2. Explicit Modeling, Functional Dimensioning and the GPS Standard

For many years, the contents, forms and definitions of standards related to technical drawings have been prepared by different technical committees, within national and international standards organizations. This has resulted in a variety of standards with different approaches and presentations. Sometimes there are contradictions; and in some cases there are gaps between the standards. That is, for example, the case with the set of standards defining the *geometric dimensioning and tolerancing system* (GD&T), which aims to accurately define and describe the geometric requirements for part and assembly geometry. The proper application of the GD&T standards will ensure that the part and assembly geometry, as defined in the mechanical drawings, leads to parts that have the desired form and fit properly in order to fulfill their function. However, because the manufacturing process will always produce workpieces which are not perfect and which show some deviation from the optimum and from one another, there is a need to measure the workpieces and to compare them with the specification in order to ensure that the physically manufactured parts will be able to fulfill the required functions. In particular, there is a need to relate the workpiece designed by the designer, the workpiece as manufactured, the knowledge of the workpiece as measured and the actual physical workpiece.

Within this context, the aim of the GPS set of standards is to define an homogeneous and complete new system, based on the inclusion into the system of the eventually revised and/or integrated existing standards and the definition of new required standards, aimed at covering the different steps of the product development process, with particular reference to the univocal specification, interpretation and control of the shape (geometry), dimensions and surface characteristics of a workpiece, together with the dispersion around the optimum where the workpiece function is still satisfactory. At present, several standards have already been redefined and inserted into the GPS system. However, others are still under revision, like the ISO 129 standard that is part of the GD&T system, in particular dealing with some basic principles of specification for dimensions and tolerances.

From an engineering practice and design/modeling task oriented viewpoint, the GPS standards introduce ideas, principles, and definitions in respect to geometric features and entities, including their spatial properties, which in turn are related to geometric constraints and functional dimensioning. In particular, the ISO 17450-1 [12] standard introduces the definition of a geometric feature as a point, line or surface; and the concept of an ideal feature is used to identify nominal features belonging to the design domain. The concepts of intrinsic characteristic, situation characteristic and situation feature are introduced additionally, in order to manage the issue of relative location among features. In order to deal with issues defined at a higher level of abstraction, the ISO 14405-1 [8] standard defines the feature of size to be a cylinder, a sphere, a cone, a wedge, or a pair of parallel surfaces. From a functional point of view, the features of size are the geometric entities providing function for coupling such as a centering hole, or guide, as used in mechanical engineering. In order to cope with situations requiring elements beyond those of linear size, ISO 14405-2 [9] has been introduced.

From a theoretical, more concept-oriented point of view, the GPS standards introduce ideas, principles, and definitions, which highlight characteristics of the distinctions among different types of dimensions. For example, a preliminary concept introduced by the GPS standards is the difference between an integral nominal element and a derived nominal element. An integral nominal element is a basic geometric element such as a line or a surface belonging to the shape of the ideal nominal representation of the part or component being designed. A derived nominal element is a geometric element such as a point, a medial axis, or a medial surface, which is computationally extracted (derived) from an integral nominal element. Size dimension, as introduced by the GPS standards, is a primary type of functional dimension. However, size dimension, as conceptualized within the first part of the ISO 14405 standard, is not the only type of dimension. Therefore, the second part of the ISO 14405 standard introduces several additional types of dimension which are structured differently (see Tab. 1) and based on a taxonomy which is oriented in part on the viewpoint of engineering practice and design/modeling tasks outlined earlier. Ideas and principles for location dimensions and orientation dimensions are conceptualized and structured under similar conditions and viewpoints.

The concept of dimension is central to the development and support of the approach and framework proposed. The concept of dimension is widely used in the standards related to technical product documentation and specification, especially in the technical drawing standards, which are aimed at defining rules and criteria for adding dimensions to a technical drawing. The GPS standards aim at defining an homogeneous framework to relate dimensioning to control procedures. In particular, the ISO 129-1 standard [7] introduces general syntactical rules and principles for dimensioning and indication of tolerances on technical drawings, whereas part 2 of ISO 129, currently in a draft form and not yet released,

Dimension		Feature characterization, type and number of			Type of dimension	Details in
Level 0	Level 1	Level 2	Level 3		Level 4	
Dimension	Linear dimension [length units]	One feature	Integral – Only features of size		Linear size	ISO 14405-1
			Integral or derived		Radius dimension	A.6, A.7, 7.4
			Integral or derived		Arc length	A.13
		Two features	Integral – integral	Facing same direction	Linear distance or step height	A.2, 7.1
				Facing opposite direction	Linear distance	A.3, 7.1, A.8, 7.5
			Integral – derived		Linear distance	A.4, 7.2
			Derived – derived		Linear distance	A.5, 7.3
		Edge (Transition region between two integral features)	Integral	Chamfer shape	Chamfer height and angle	A.12
				Rounding shape	Edge radius	A.12
	Angular dimension [angle units]	One feature	Integral – Only features of size		Angular size, Cones	ISO 3040
		Two features	Integral – integral		Angular distance	A.9, 7.7
			Integral – derived		Angular distance	A.11, 7.8
			Derived - derived		Angular distance	No example

Tab. 1: Overview of concepts used to define different types of dimensions as reported in the GPS standards (adapted from [9], p.3).

is expected to introduce specific cases of particular interest for the field of mechanical engineering. The GPS standards introduce additional concepts and definitions aimed at relating dimensions and tolerances specified in the nominal domain of representation to the control of dimensions and tolerances in the real domain of verification. In particular, ISO 14660-1 [11] introduces the concepts of integral element and derived element. Those concepts are used in ISO 14405-1 [8] to define the type of size dimension and in ISO 14405-2 [9] to classify types of dimensions and to define dimension types other than size, including location and orientation dimensions. The underlying concepts of the GPS standards relate the definition of functional requirements within product development processes to geometrical specification using various types of dimensioning. However, the concept of dimension has a different role in the context of MCAD systems and their use. Here dimensions are defined and implemented to drive the alteration of geometry (driving dimensions) or to dynamically label dimensions (driven dimensions). In particular, within feature-based modeling systems, dimensions are mainly related to individual features, whereas within direct/explicit modeling systems the dimensions are related to the global shape of the model.

Dimensions and tolerances as defined and employed in the standards discussed above are a means of expressing and documenting engineering functions. In the approach introduced in this paper, such concepts are used to develop a framework based on functional as well as non-functional dimensioning features. This facilitates the translation of functional modeling into best practices aimed at preserving the design intent through concept mapping and implementation based on functionality and commands provided by the user interface of commercially available direct/explicit MCAD systems. An overview of the structure and scheme of the proposed approach, together with the role of the different concepts used, is shown in Fig. 1.

3.3. The Concept of Functional Dimensioning Features

In the following, the general concept of dimensioning features (DF) is introduced, together with its more specific sub-concepts, namely functional dimensioning features (FDF), non-functional dimensioning features (NFDF), and auxiliary dimensioning features (ADF). Note that details will be discussed on each occasion in regard to one sub-type only, in most cases the FDF. This is because further exemplification is rendered superfluous by the consistency of the corresponding concepts, which define components in the specific sub-concepts and relate them to their counterparts in the more general DF concept. The DF concept is structured around three basic components comprising geometry, spatial property, and distance, and these are related to both explicit and implicit entities. From a theoretical point of view, this structure relates to entities, their properties, and a metric on the entity space.

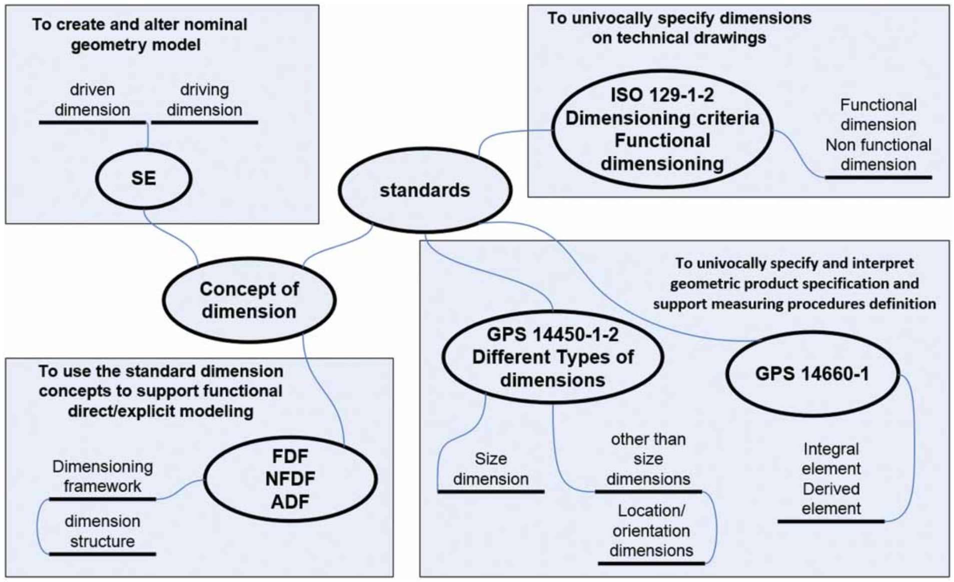

Fig. 1: Outline of concepts and relationships.

Geometry within all dimensioning feature concepts is sub-divided into explicit geometry and implicit geometry. Explicit geometry consists of sized geometry and non-sized geometry, referring to basic geometric elements such as vertices, edges, and surfaces, as commonly found within the boundary representation of a CAD model and also employed within the GPS standards for concepts of features of size and linear dimensions (cf. [8]). Entities of explicit geometry are always actual elements of the shape of a designed part or assembly, as defined by a CAD model. Implicit geometry is sub-divided into derived and referenced geometry. Size within FDF sized integrated geometry consists basically of three structural components, namely a linear or angular size parameter value, geometric constraints and auxiliary geometry. Derived geometry consists of basic geometric entities, such as points, lines, and planes, which are required for functional dimensioning and can be derived from any geometry that can be referenced. For example, the center-line of a hole modeled as a cylindrical depression within a CAD model can be derived from its associated geometric boundary elements, namely the cylindrical surface and its related circular edges at its ends. Derived geometry can be singular if the derivation is based on one geometric entity or multiple if derivation is based on several entities. The number of derivations is identified by the degree of derived geometry. The center-line of a hole being derived from its integral geometry represents first degree derived geometry, while a spatial pattern derived from a set of center-lines represents (multiple) second degree derived geometry. Referenced geometry is comprised of basic geometric entities similar to derived geometry, though direct reference relationships are used instead. Such geometric entities might include a portion from the shape definition conceptualized as integral geometry within the GPS standards, or elements used for modeling, such as reference planes, that are not part of the shape definition and are therefore identified as non-integral geometry, or elements that are created by the user as defined reference geometry. For example, two planes required for dimensioning a linear distance according to definitions of the GPS standard (cf. [8]) can be represented within implicit referenced geometry by being related to two face entities of the boundary representation of the CAD model. At this point it is important to note that referenced geometry also contains user-defined basic geometric elements, which are not explicit elements of the shape defining geometry within a CAD model. This requirement arises from auxiliary geometry necessary to define constraints. For example, symmetry planes are employed to specify the symmetry constraints that are required in some cases for properly dimensioning linear size features and/or distances in accordance with the concepts of the GPS standards. The concept of distance within functional dimensioning features is abstracted according to linear dimensions other than size and location/orientation as described in GPS standards. Within this framework, the concept is comprised of linear/angular distance parameter values, which are associated with FDF geometry.

Spatial properties within all dimensioning feature concepts are sub-divided into explicit spatial properties and implicit spatial properties, in order to provide adequate concepts regarding location and orientation of geometric elements for each geometry class considered, namely explicit geometry and implicit geometry. Explicit spatial properties, associated with elements of explicit geometry, consist of entity location and entity orientation, which are employed to express the location and orientation of designated geometric elements used within functional dimensioning. The structure is oriented on the situation characteristics defining location and orientation in terms of distances and angles among points, lines, and planes as described in [9]. Implicit spatial properties, associated with elements of implicit geometry, consist of entity location and entity orientation employing structures similar to those of their counterparts within explicit spatial properties. However, within implicit spatial properties, mechanisms to associate basic geometric elements and compute their actual spatial properties in terms of location and orientation are different, as one has to deal with derived or referenced geometric elements, which are usually not explicitly available within a CAD model, since they are not part of the actual shape definition.

Distance within functional dimensioning features is abstracted as a concept according to linear dimensions other than size and location/orientation as described in the GPS standards. Within this framework, this concept is comprised of linear and angular distance parameter values, which are associated with geometry within the general DF concept and its more specific sub-concepts, i.e. FDF, NFDF, and ADF.

4. FRAMEWORK TRANSLATION AND APPLICATION EXAMPLE

4.1. Overview

If we consider technical drawing as a kind of graphical language, we can regard its standards as defining the syntactical rules for specifying, among other things, the dimensions. Here the semantics associated with the technical drawing are defined by specific sets of dimensions, which a designer will specify among all sets possible, as allowed by syntactic rules. The main criterion used by designers for specifying dimensions is functional dimensioning (and an example of an alternative dimensioning criterion is technological dimensioning). Functional dimensioning is aimed both at supporting component interchangeability and at ensuring that components are manufactured with adequate precision in respect to the functions which they are required to fulfill. Hence, functional dimensioning reflects the requirements that define specific behavior or the functions which a component must have. Within functional dimensioning, different types of dimensions need to be considered, namely functional dimensions, non-functional dimensions, and auxiliary dimensions. Functional dimensions are the dimensions related to functional geometric elements and they are often associated with specific tolerances, representing what the component is supposed to do. Non-functional dimensions are those dimensions, which are required to complete the dimensioning of the component and they are usually associated with general tolerances representing properties of how a component is supposed to be. Auxiliary dimensions are additional dimensions, specified as labels aimed at making the drawing easier to read and they are not related to tolerances. Later on, in the section on examples and implications, actual examples of different dimensions are analyzed and discussed in detail. An overview of these examples is shown in Fig. 3 and is comprised of functional dimensions depicted in red and blue, non-functional dimensions depicted in black and cyan, and an auxiliary dimension (in brackets) depicted in magenta.

The criteria considered central to functional dimensioning are the following. First, specific precision is required for the manufacturing of all the functional elements involved in the coupling of components. The precision required is specified in the drawing by using dimensions and related tolerances. Second, standard precision is required for the manufacturing of all the remaining functional elements. Standard precision is specified in the drawing by using dimensions and general tolerances. Finally, all additional dimensions required to univocally define the component size must be specified in the drawing. According to engineering practice and use of the standards discussed elsewhere in this paper, functional dimensioning criteria can be translated into application as follows:

1. Identify the functional elements that will require specific tolerances.
2. For each functional element with specific tolerances, add the size dimensions or linear dimensions.
3. For each functional element with specific tolerances, add location/orientation dimensions, if required.
4. Identify the functional elements that do not require specific tolerances.
5. For each functional element without specific tolerances, add the size dimensions or linear dimensions.
6. For each functional element without specific tolerances, add location/orientation dimensions, if required.
7. Add the dimensions (size, linear, location/orientation) required to complete the dimensioning.
8. Add auxiliary dimensions, if required.

Functionality and commands as provided by the user interface of current direct/explicit systems provide a new approach to 3D modeling in the sense that traditional design criteria can be translated on a more explicit basis into best practice for modeling, with several benefits for both industrial practice and education. From a practical point of view, criteria related to fully dimensioning a design will support the definition of a fully constrained 3D model. In particular, the application of the functional dimensioning criteria in 3D modeling will add semantics to the geometric model and also help in preserving the design intent during model alteration. Moreover, the definition of functional dimensions carried out directly on the 3D model will improve support of the definition and compilation of 2D technical drawings. From an educational point of view, an improved analogy between concepts and criteria considered central to both engineering design and computer-aided modeling allows for a better, more effective and more efficient use of CAD systems as supporting tools in the teaching of modern design methodologies.

4.2. Context and Settings

In order to validate the proposed approach, while verifying related advantages and analyzing limitations, we have selected the commercially available parametric CAD system *Solid Edge ST6* from Siemens, referred to as *SE* in the following. This system has been employed for example model implementation and empirical work. Although most, if not all, commercially available MCAD systems supporting explicit modeling are based on the same theoretical approach, some differences exist in relation to how basic concepts have been translated into system-internal data structures and actual commands provided within the user interface. SE supports both feature-based modeling (ordered modality) and explicit modeling (synchronous modality). In the synchronous modality, SE provides commands which define and select planes whereon 2D profiles can be sketched that will define the regions that can then be extruded and twisted to add or remove volumes to the 3D model. During modeling operation, SE automatically captures basic geometric constraints, such as perpendicularity of surfaces extruded in respect to the reference sketching plane, and dimensional constraints like the height of an extrusion. Additional geometric constraints, such as symmetry and co-planarity of planar surfaces, and co-axial conditions of cylindrical surfaces, can be added explicitly by the user. Dimensional constraints can also be added in the form of linear and angular driving dimensions. Driving dimensions can be used to alter the model size. Additional interactive model alteration can be performed by taking advantage of the so-called *driving wheel*, which is an interactive tool that the user can place on geometric entities to perform alteration by means of surface translation and rotation. Model alteration is limited by geometrical and dimensional constraints related to the model. Incoherent and conflicting constraints can be suppressed by the user through interaction with so-called *live rules*, or by changing a driving dimension into a driven dimension, to enable the CAD system to compute and finalize the model alteration previously blocked.

Our analysis of the explicit modeling functionality and commands available at the user interface of SE concludes that they are generally consistent with corresponding concepts and functional structures of the FDF framework developed. However, some basic functionality and concepts are still missing, and this is seen as a potential system limitation impeding a consistent and complete implementation of functional dimensions. This is in part due to the definition of integral and derived elements in the GPS standards. In particular, an integral nominal element is defined as a line or a surface belonging to the ideal geometry of the represented component, and a derived nominal element is defined as a geometric element extracted (derived) from an integral element (e.g. a point, a medial axis, or a medial surface). Here integral and derived elements are used as references to define functional dimensions, with derived elements mainly being used as the references for location/orientation dimensions. However, CAD systems do not provide a means of consistently representing, maintaining, and accessing both integral geometry and reference geometry at the user interface, though several cases exist where implicit geometric elements, i.e. entities which are not part of the shape definition, are employed internally by CAD systems to execute modeling commands.

By taking into account functionality and the commands provided by the explicit modeling user interface of the experimental system setting as outlined above, functional dimensioning criteria as listed earlier can be mapped into a set of best practice to appropriately formulate constraints for the model as follows:

- Add a diameter driving dimension to the cylindrical feature of size.
- Add a driving linear dimension and a symmetry constraint to the planar feature of size. Be sure to impose a symmetric modification when altering the dimension.
- Add a linear or angular driving dimension to locate/orient the feature of size. Be sure to select the appropriate entity when defining the dimension. Remember to select the appropriate reference element when altering the dimension.
- Add a linear or angular driving dimension to define features other than the feature of size. Check that appropriate geometric constraints are related to the reference elements for dimensions. Be sure to select the appropriate reference element when altering the dimension.
- Add driven dimensions to define the required auxiliary dimensions.

In the next sub-section, an example will be presented and discussed with the aim of describing in more detail how individual functional dimensioning criteria can actually be mapped into best practice for explicit modeling through translation into and implementation of FDF concepts and structures.

4.3. Examples and Implications for Education and Practice

We applied the method, and the framework developed and described earlier in this paper, to the design and complete dimensioning of a rigid joint fixture. This circular rigid joint fixture is used to inflexibly connect two shafts for transmitting torque. The joint housing and its parts, selected from within the application domain of mechanical engineering, represent an actual industrial product, which is manufactured using die casting and machining. In order to keep the example transparent, with a focus on the concepts central to the approach, rounds and chamfers are omitted in both the CAD model and the specification of dimensions. Details of part and product geometry are shown below (cf. Fig. 2) as rendered screen dumps created within our implemented modeling example.

As a reference for the example discussed, a section of the 2D technical drawing with the fully dimensioned joint fixture is shown in Fig. 3. Functional dimensions of size are colored in red, functional (linear) dimensions other than size are colored in blue, non-functional dimensions both of size and other than size are colored in black, and non-functional dimensions that are angular dimensions related to manufacturing technology are colored in cyan. The auxiliary dimension is colored in magenta. The reference circumference is indicated in green.

4.4. Functional dimensioning related to size

On the part subject to dimensioning, four functional dimensions of size can be identified, namely the diameter of the hole for the coupling with the shaft, the diameter of the centering pocket hole, diameters for the four joint fixture holes and the width of the key housing. They can be defined using FDF concept structures and CAD system elements as described below. In the case of the pocket hole, the four through holes, and the shaft hole, the diameters are all linear size dimensions that can be directly related to corresponding elements within explicit sized geometry of the FDF, in this example circular surfaces. Each of these in turn refers to concrete elements of the shape of a designed part as defined by the CAD model. Note that here diameter value constraints can be added to the four joint fixing holes.

In the case of the width of the key housing (see Fig. 3(a) and Fig. 4(b)), correct size dimensioning requires, besides explicit sized geometry and a linear size parameter value, auxiliary geometry and geometric constraints as provided by the FDF size dimension within sized integrated geometry. This requirement is due to the characteristics associated with functional dimensions of size such as the width of the key housing. These dimensions contain symmetry conditions defining the width as a linear distance between two parallel surfaces with their normal vectors oriented

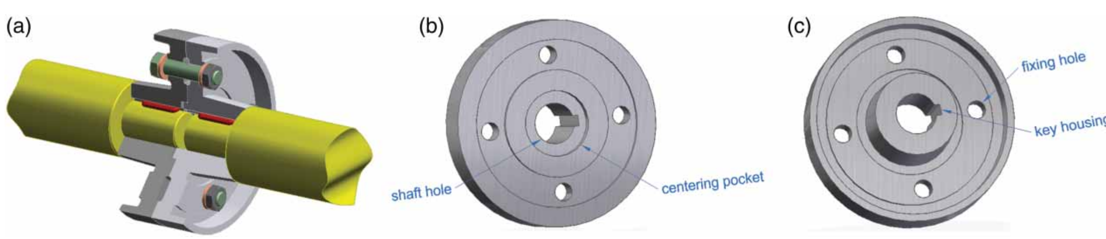

Fig. 2: Examples of the rigid joint fixture. From left to right: (a) assembly with cross section, (b) left side of the joint fixture part, and (c) right side of the joint fixture part.

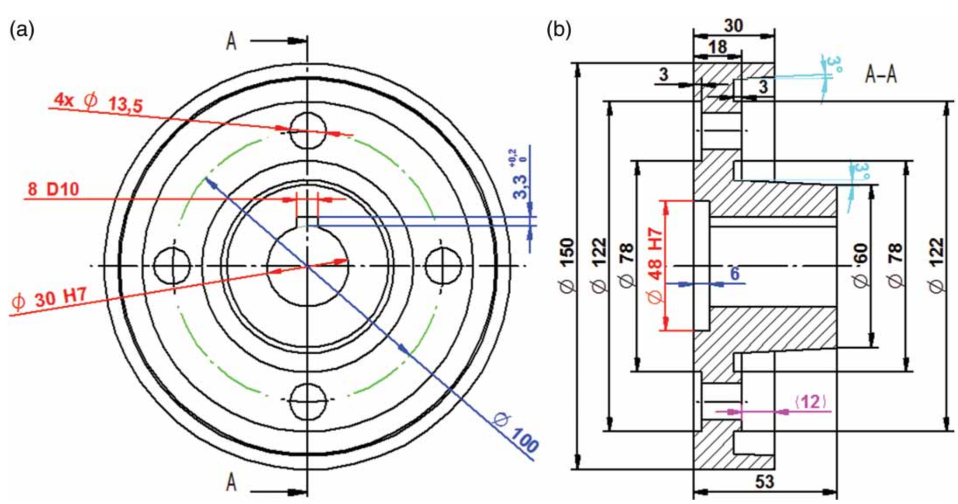

Fig. 3: The rigid joint fixture fully dimensioned. From left to right: (a) left side of the joint fixture part, and (b) cross section of the joint fixture part.

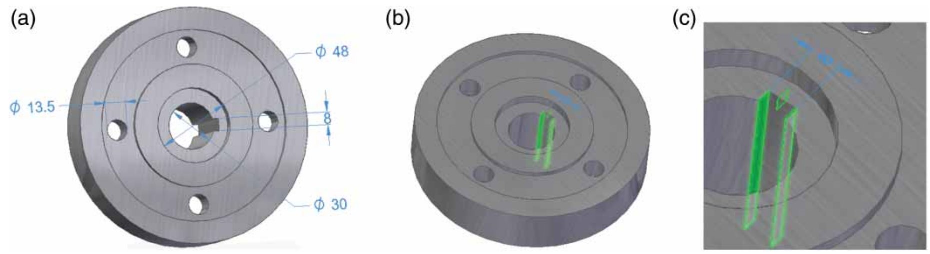

Fig. 4: Examples of the left side of the rigid joint fixture part. From left to right: (a) functional dimensions related to size, (b) referenced geometry of the key housing, and (c) enlarged section view depicting details of the referenced geometry of the key housing.

towards a symmetry plane in the middle (cf. [9] and Tab. 1).

For such a functional dimensioning scenario, CAD systems do not automatically provide either the auxiliary geometry in the form of a planar symmetry surface (see Fig. 4(c)) or associated geometric constraints ensuring that this symmetry condition is met. Therefore, necessary geometric elements, constraints, and references to explicit geometry have to be created and added manually by the user. This can be achieved within the experimental setting by employing the explicit modeling interface and geometric constraints. The location and orientation of functional dimensioning features can be captured by the FDF explicit spatial property in association with symmetry planes of the CAD model. In the case of the width of the key housing, the vertical symmetry plane can be used. In the case of the diameter of the centering pocket hole, the line of intersection of the vertical symmetry plane and the horizontal symmetry plane can be used.

In the case of the four joint fixture holes, entity orientation can be associated with elements within live rules, where the perpendicularity of central axes of individual holes and respective entrance faces in respect to model-internal symmetry planes is maintained by the CAD system (see Fig. 5(a)). The entity location can be defined as the intersections between model-internal symmetry planes and a reference circumference. As this kind of entity location in respect to reference geometry is only implicitly maintained by the system if a pattern of elements is recognized, the user must explicitly employ pattern commands during modeling or apply the pattern recognition command before being able to access location dimensions (see also Fig. 5(b)).

4.5. Functional dimensioning related to distance and spatial property

On the part subject to dimensioning, three functional dimensions other than feature of size can be identified, namely the depth of the centering pocket hole, the depth of the key housing, and the diameter of the reference circumference. The depth of the centering pocket hole can be defined using the functional dimensioning features as a linear dimension translated into a distance between two parallel surfaces (cf. linear step feature in [9]). At this point it should be emphasized again that, according to the GPS standards and FDF structures, depth dimensions are conceptually different from size dimensions. Therefore auxiliary geometry in the form of user-created symmetry planes, as discussed above, is not required, though parallelism of the two surfaces used to define the linear dimension needs to be maintained.

To solve the ambiguity related to the change in the shape of the centering pocket hole, depending on whether depth (see Fig. 6(a)) is modified towards

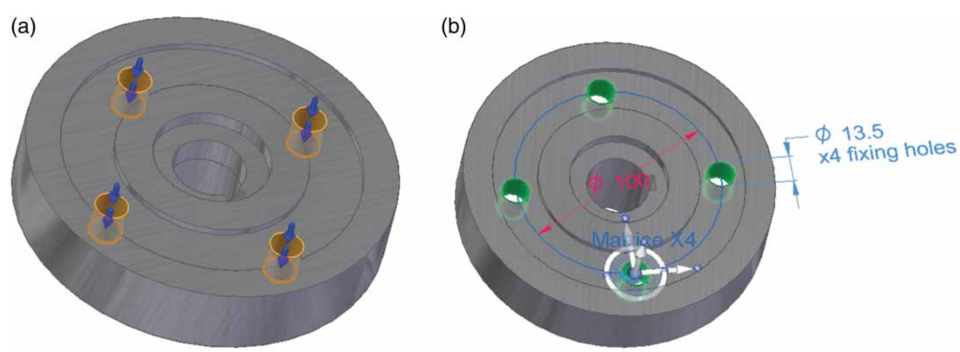

Fig. 5: Examples of the left side of the rigid joint fixture part. From left to right: (a) entity orientation and derived geometry of the four joint fixture holes, and (b) spatial pattern and reference geometry of the four joint fixture holes.

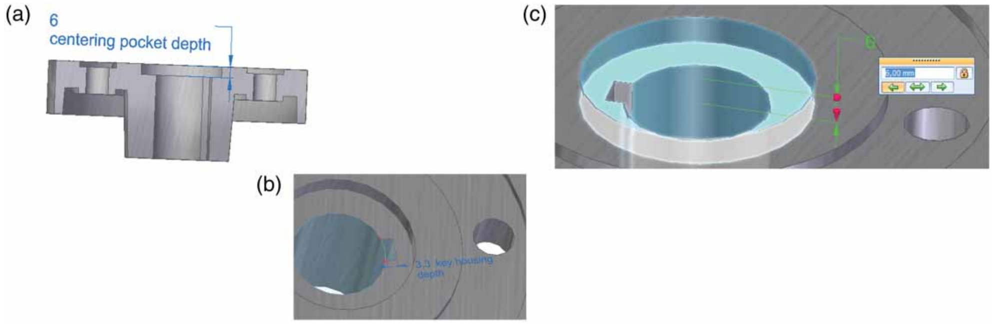

Fig. 6: Examples of the right part of the rigid joint fixture. From left to right: (a) cross sectional view showing details of the centering pocket hole, (b) enlarged section view depicting details regarding the linear dimensioning of the depth of the key housing, and (c) enlarged section view depicting details of the reference geometry and selection of the modification direction during linear dimension setting.

the top or the bottom face of the pocket hole, a reference surface conceptualized as FDF implicit reference geometry needs to be specified by the user and associated with this linear dimension. This can be achieved within the experimental setting through the explicit modeling interface by selecting the modification direction while setting an actual value for the dimension (see Fig. 6(c)). The depth of the key housing (see Fig. 6(b)) can be defined using functional dimensioning features as a linear dimension translated into an FDF distance (linear) between two elements of FDF reference geometry. However, due to current system limitations and the inability to define any reference geometry that can be associated with the CAD model employing the functionality provided at the user interface, a functional dimension for the depth of the key housing consistent with the framework cannot be implemented with this CAD system yet. The diameter of the reference circumference, which can be described by FDF referenced geometry and a linear parameter, cannot be placed directly on the 3D model, due to the inability of the CAD system to automatically produce appropriate reference geometry unless a hole pattern command has been evoked previously.

4.6. Non-functional dimensioning related to technology and completion of dimensioning

Non-functional dimensions are considered constraints or quality attributes that relate to properties which define how a part or component is supposed to be. This is different from functional dimensions, which define what a part or component is supposed to do. Within the example context, we considered only non-functional dimensions related to the manufacturing of a part. Regarding the manufacturing technology used, draft angles (set to 3^0) required by the casting process are introduced as shown in Fig. 3(b). Those draft angles can be defined as angular size parameters within NFDF explicit geometry. However, due to current system limitations and the inability to define any geometry that can be associated with the CAD model employing explicit modeling, non-functional dimensions in the form of draft angles also cannot be implemented with this CAD system, unless explicit draft modeling operations are used. Non-functional dimensions to complete the dimensioning (see again Fig. 3(b)) can be defined as linear size parameters within NFDF explicit geometry and as linear distances within NFDF implicit geometry. They can be directly placed as driving diameter dimensions on the 3D model using functionality provided by the explicit modeling user interface. Notice that in this last example, the diameter dimensions, although structurally equivalent to the size dimensions defined within the functional dimensions of the GPS standards, are defined and implemented as size parameters of non-functional explicit geometry, because there will be no explicit tolerances required for their manufacturing, thus rendering them semantically as non-functional.

5. CONCLUSIONS AND FUTURE WORK

A novel framework has been presented and discussed, aimed at supporting a methodological approach to explicit modeling by using functional dimensioning criteria. This has been approached by means of an integrative correspondence between dimensioning concepts, as specified by the ISO mechanical drawing standards, and the operative framework, as provided by explicit modeling. Here the concept of functional dimensioning features has been developed as a notion, and as a basis for providing principles and structures for the framework. The route taken to define the proposed methodology started with the analysis of concepts, criteria and entities related to functional dimensioning, as provided by the standards, with particular reference to the ISO GPS set of standards. In parallel with this analysis, the commands and functionality provided by the explicit modeling user interface of a commercially available MCAD system have been investigated.

As was shown by both theoretical analysis and the results of empirical work, at present the dimensioning concepts, as defined by the standards, and the explicit modeling functionality for dimensioning available within the MCAD system, are neither sufficiently structured nor coherent enough to allow for sound and complete 3D functional dimensioning, as traditionally applied in mechanical engineering. It is in this context that the newly developed concept of functional dimensioning features comes into prominence. The principles and structures of this concept are capable of explicitly representing all the nominal entities introduced by the ISO GPS standards, such as integral and derived geometric entities, for example. These nominal entities are essential to the implementation of central concepts such as features of size, situation features, and intrinsic characteristics, which in turn are required in order to perform functional dimensioning of a mechanical part or component. Functional dimensioning features are also used to represent additional geometric elements, such as referenced and auxiliary entities, required to support functional dimensioning and to enable and implement functional dimensioning using explicit modeling within modern MCAD systems. From an educational point of view, taking into account functionality and commands provided by the explicit modeling user interface of the reference system used, functional dimensioning criteria have been mapped into a set of best practice to define appropriately constrained 3D explicit models.

The proposed framework has now been included on an experimental basis within current CAD courses for mechanical engineering students, offered by the department represented by the authors. The experiments currently in progress are aimed at increasing, through empirical data and evidence, understanding of the role of, and interrelated relationship between, strategic and procedural knowledge regarding both the use of explicit modeling systems and the support for teaching of mechanical design principles, in particular the known correspondence between mechanical functions and geometric shapes.

REFERENCES

[1] Bhavnani, S. K.; Reif, F.; John, B. E.: Beyond Command Knowledge: Identifying and Teaching Strategic Knowledge for Using Complex Computer Applications, CHI 2001, ACM Conference on Human Factors in Computing Systems, CHI Letters, 3(1), 229–236.

[2] Danjou, S.; Lupa, N.; Koehler, P.: Approach for Automated Product Modeling Using Knowledge-Based Design Features, Computer-Aided Design and Applications, 5(5), 2008, 622–629, doi:10.3722/cadaps.2008.622-629.

[3] Dantana, J.Y.; Ballub, A.; Mathieuc, L.: Geometrical Product Specifications - Model for Product Life Cycle, Computer-Aided Design, 40(4), 2008, 493–501, doi:10.1016/j.cad.2008.01.004.

[4] Desrochers, A.; Clément, A.: A Dimensioning and Tolerancing Assistance Model for CAD/CAM Systems, International Journal of Advanced Manufacturing Technology, 9(6), 1994, 352–361.

[5] Germani, M.; Mandorli, F.; Mengoni, M.; Raffaeli, R.: CAD-Based Environment to Bridge the Gap between Product Design and Tolerance Control, Precision Engineering, 34(1), 2010, 7–15, doi:10.1016/j.precisioneng.2008.10.002.

[6] Hillyard, R. C.; Braid, I. C.: Analysis of Dimensions and Tolerances in Computer-Aided Mechanical Design, Computer-Aided Design, 10(3), 1978, 161–166.

[7] ISO 129-1:2004 – Technical Drawings – Indication of Dimensions and Tolerances - Part 1: General Principles.

[8] ISO 14405-1:2010 - Geometric Product Specification (GPS) – Dimensional Tolerancing - Part 1: Linear Sizes.

[9] ISO 14405-2:2011 - Geometric Product Specification (GPS) – Dimensional Tolerancing - Part 2: Dimensions other than Linear Sizes.

[10] ISO-DIS 14638:2012 – Geometric Product Specification (GPS) – Masterplan.

[11] ISO 14660-1:1999 - Geometric Product Specification (GPS) – Geometrical Features - Part 1: General Terms and Definitions.

[12] ISO 17450-1:2011 - Geometric Product Specification (GPS) – General Concepts – Part 1: Model for Geometrical Specification and Verification.

[13] Iyer, G. R.; Mills, J. J.: Design Intent in 2D CAD: Definition and Survey, Computer-Aided Design & Applications, 3 (1–4), 2006, 259–267, doi:10.1080/16864360.2006.10738463.

[14] Jagenberg, J. T.; Gilsdorf, E. A.; Anderl, R.; Bornkessel, T.: Knowledge Driven Design Features for the Product Life Cycle of Engine Parts, In Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 30 – September 2, San Diego, CA, USA, Vol. 8, 2009, 721–728.

[15] Light, R.; Gossard, D.: Modification of Geometric Models Through Variational Geometry, Computer-Aided Design, 14(4), 1982, 209–214.

[16] Ma, Y.-S.; Tong, T.: Associative Feature Modeling for Concurrent Engineering Integration, Computers in Industry, 51(1), 2003, 51–71, doi:10.1016/S0166-3615(03)00025-3.

[17] Mandorli, F.; Cugini, U.; Otto, H. E.; Kimura, F.: Modeling with Self Validation Features, In Proceedings of the ACM Symposium on Solid Modeling and Applications, May 14-16, Atlanta, GA, USA, 1997, 88–96, doi:10.1145/267734.267757.

[18] Mengoni, M.; Germani, M.; Mandorli, F.: Reverse Engineering of Aesthetic Products: Use of Hand-Made Sketches for the Design Intent Formalization, Journal of Engineering Design, 18(5), 2007, 413–435. doi:10.1080/09544820701403748.

[19] Otto, H. E.: From Concepts to Consistent Object Specifications: Translation of a Domain-Oriented Feature Framework into Practice, Journal of Computer Science and Technology, 16(3), 2001, 208–230, doi:10.1007/BF02943200.

[20] Rynne, A.; Gaughran, W.: Cognitive Modeling Strategies for Optimum Design Intent in Parametric Modeling, Computers in Education Journal, 18(3), 2008, 55–68.

[21] Shah, J.; Mantyla, M.: Parametric and Feature Based CAD/CAM: Concepts, Techniques, and Applications, John Wiley & Sons, New York, NY, USA, 1995.