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Comparing 3D CAD Models: Uses, Methods, Tools and Perspectives

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ABSTRACT

With the advancements of 3D modeling software, the use of 3D CAD in mechanical product design has become a standard practice. Methods and tools are continually being developed to improve designers’ efficiency in the creation, modification and analysis of 3D CAD models. Among other advantages, comparing 3D CAD models to assess their relative shape similarity or to identify their differences leads to benefits in various CAD- and PLM-related areas such as design reuse, engineering change management and data exchange. As 3D data continues to be more frequently and intensively shared and used in the mechanical product development process (PDP), this paper describes the subject of 3D CAD model comparison from three related points of view. First, it organizes the wide variety of use cases for 3D CAD model comparison into specific application domains. Difference calculation methods and approaches are compared, identifying their key characteristics and limitations. Then, it presents an inventory of commercially available software tools that perform 3D CAD model difference identification (MDI). Finally, some research perspectives for 3D CAD model comparison applied to shape change transposition are contemplated.

Keywords: 3D CAD model comparison, difference calculation, product data reuse.
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1 INTRODUCTION

Today’s product lifecycle management (PLM) solutions address the contemporary challenges of collaborative and integrated product development. The management, storage and distribution of the geometric definition of a product relies on 3D data, data that is being more frequently and intensively shared and used than ever before. For example, 3D CAD models are increasingly used as inputs to retrieve and compare products, parts and related information from PLM vaults to ultimately enable product data reuse, and/or to otherwise leverage the knowledge associated with this type of document and the data it encloses.

Three-dimensional (3D) CAD model comparison is defined here as the process of calculating and representing the differences or similarities between 3D CAD models embodying the geometric definition of mechanical parts. 3D CAD model comparison has been the focus of several advancements in the last decade, notably in the field of 3D shape-based retrieval [11], [32], [38], [57], [68]. In contrast, developments regarding the pair-wise comparison of 3D CAD models designed for the location and documentation of differences have remained sparse, mostly originating from standardization schemes [13], [26] or 3D CAD software developments [20]. However, the process of comparing 3D CAD models does bring a variety of benefits to multiple scenarios in the development of mechanical products.

This paper falls within the framework of a research project that addresses the subject of *shape change transposition* between heterogeneously formatted 3D CAD models. For example, in Fig. 1, an initial reference model released as a STEP file from Design Engineering defines a part's original geometry. An initial target CAD/CAM model is created by Manufacturing Engineering as per the initial reference model in a format deemed appropriate for manufacturing planning (e.g. procedural modeling such as NX® [41]). Then, an engineering change order (ECO) calls for the release of a modified reference model, derived from the initial reference model. To derive a modified target CAD/CAM model from the initial target model, Manufacturing Engineering must therefore identify the exact shape change through model comparison and transpose this shape change in the manufacturing domain. The global objective of this research project is to develop a 3D CAD model comparison method for shape change transposition, in which the representation of the differences is intended to optimize their interpretation and their integration by the process responsible for updating the initial target model and, thus, deriving the modified target model. Previous work on the identification and representation of 3D CAD model comparison scenarios like this one is described in [9].

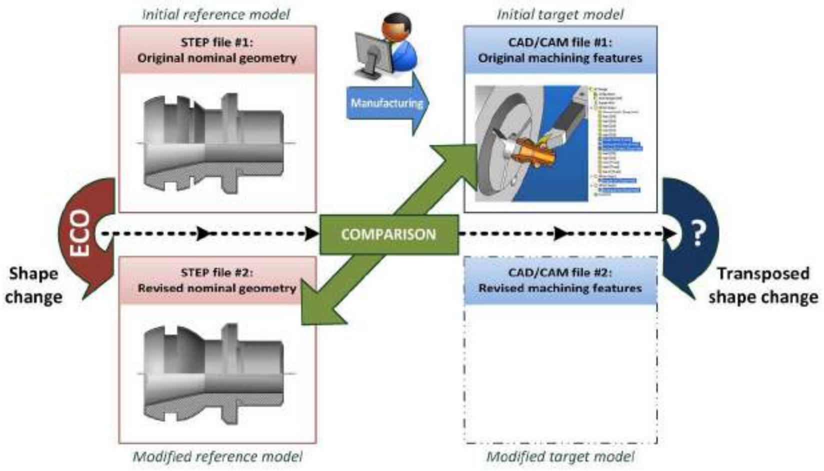


Fig. 1: Sample scenario of shape change transposition: Updating a CAD/CAM model based on revised geometry.

With the specific objective of identifying and organizing existing literature and recent developments in this promising CAD- and PLM-related domain and, thereby, of laying the groundwork for our research project, this paper presents a comprehensive review of current research and developments in 3D CAD model comparison from three perspectives: the uses, the software tools and the methods. Section 2 presents a survey of 3D CAD model comparison scenarios, categorizing different use cases. Difference calculation methods are characterized in Section 3. Pair-wise 3D CAD model comparison is then the focus, as an inventory of existing software tools implementing 3D CAD model difference identification (MDI) is described in Section 4. Finally, research perspectives are contemplated in Section 5.

2 USE CASES OF 3D CAD MODEL COMPARISON

As the first part of this article, an exploratory survey makes a broad inventory of scenarios involving the comparison of 3D CAD models as they are exposed in CAD- and PLM-related documentation and research literature. As summarized in Table 1, 3D CAD model comparison use cases can be organized into six major application domains and related to three solution domains: (1) shape-based retrieval, (2) equivalence/similarity assessment, and (3) difference identification.

		Solution domain		
Application domain	*Use case*	*Shape-based retrieval*	*Equivalence/similarity assessment*	*Difference identification*
Product information reuse	▪ Design concept ▪ Manufacturing process ▪ Simulation/analysis data ▪ Pricing information ▪ Sourcing information ▪ Qualification tests results	X		X
Product rationalization and standardization	▪ Eliminate duplicate parts ▪ Improve sourcing ▪ Form part/product families ▪ Find interchangeable parts ▪ Identify common platforms ▪ Identify differentiation enablers ▪ Verify interchangeability	X	X	X
CAD modeling management	▪ Prevent model duplication ▪ Promote modeling best-practices	X		
CAD data translation/remastering	▪ CAD migration ▪ CAD data exchange ▪ CAD interoperability ▪ Long term archival		X	
CAx models authoring	▪ CAM models ▪ FEA models		X	
Engineering change management	▪ Change documentation ▪ Impact analysis ▪ Change transposition ▪ Change propagation ▪ Evolution control			X

Tab. 1: Application domains, use cases and solution domains for 3D CAD model comparison.

2.1 Identifying the Solution Domains

As pictured in Fig. 2, the three solution domains for the inventoried use cases were determined, based on the two key aspects that characterize 3D CAD model comparison problems:

- *Cardinality* ð a reference model may either be compared to one single target model (1:1, or *pair-wise*) or to many models (1:n) usually from large sets; and

- *Level of detail* ð the amount of information expected from the comparison, which will vary according to the intended use, ranging from a simple òYes-Noó or òPassed-Failedó diagnosis to detailed measures of the differences between the compared models.

Higher cardinalities require higher computational efficiency, since it regulates the quantity of comparisons to be performed in a single operation. Similarly, higher levels of details understandably call for more detailed difference calculation algorithms and, consequently, more complex difference representation schemes. Accordingly, we defined a relation between the level of detail and the cardinality, allowing us to identify six different basic functions for comparing 3D CAD models (see Table 2). Each basic function relates to an elementary question that the 3D CAD models comparison is expected to answer, and provides insight on what type of result is expected.

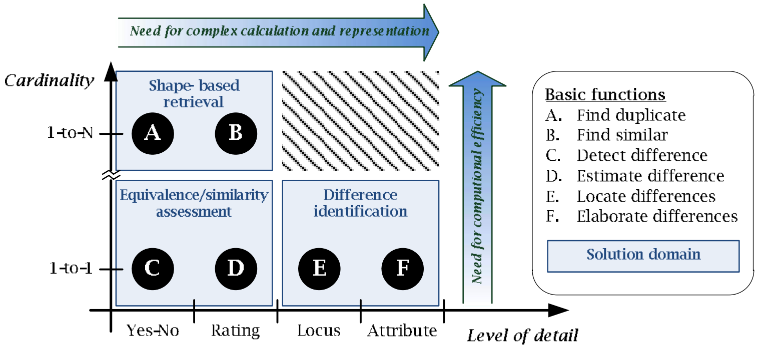


Fig. 2: Solution domains and basic functions as a relation between the required level of detail and cardinality.

	Basic function	*Basic question*	*Expected result*
A.	Find duplicate	Which models are equivalent?	Finite sets of objects
B.	Find similar	Which models are similar?	Ordered, scale-based distributions
C.	Detect difference	Are the models different?	Binary results (Yes/No, Pass/Fail, etc.)
D.	Estimate difference	How different are the models?	Qualitative, global, scale-based measures
E.	Locate differences	Where are the differences?	Graphical reports, loci, regions
F.	Elaborate differences	What are the differences?	Classifications, local measures, descriptions

Tab. 2: Basic functions of 3D CAD model comparison.

The three solution domains organize these basic functions. Verifying two modelsô equivalency according to some explicit criteria or estimating their relative similarity with use of a metric, i.e. providing a qualitative appraisal of how close or different they are from each other, involves equivalence or similarity assessment. Shape-based retrieval achieves finding duplicate or similar models with the use of the comparable similarity measures, but within large sets of 3D CAD models simultaneously. Finally, to distinguish individual differences between two models, providing their respective locus in relation with the modeled shapes or, furthermore, a detailed description of their characteristics, we refer to the identification of the modelsô differences.

2.2 Product Information Reuse

To achieve the desired goal of reducing costs and delays while lowering risk, one aspect of PLM features the retrieval and reuse of parts, products and associated information. 3D CAD model comparison is key to overcoming the challenge, as shape itself can now be perceived as a neutral and effective language to represent and retrieve product data in PLM vaults [38].

It is now possible to quickly compare quite large numbers of 3D shapes to each other through the use of lightweight pre-computed shape descriptors or signatures, as many research and survey papers have so indicated ([11], [32], [38], [57], [68]). A 3D CAD model selected as a search key can be compared to other models in order to assess their similarity via a given metric which, in turn, will be used to identify, rate and sort a subset of the compared models that can be considered similar. Particularly, feature-based techniques for shape-based retrieval, such as those described by Cicirello and Regli [18], Bai et al. [8] or Chu and Hsu [17], enable part and/or model function to be involved in the similarity assessment of candidate models, which is a considerable aspect in product information reuse.

Most of the published works present the reuse of existing product information as the main application of their respective approaches to shape-based retrieval. A benchmark on product design reuse conducted by the Aberdeen Group [33] validates this trend by revealing that, while 46% of the surveyed manufacturing organizations identify information retrieval as a challenge, the best-in-class organizations in terms of reuse are three times more likely to have made use of shape-based searches. Msaaf et al. [40] reported on the potential uses for shape-based retrieval tools for product information reuse, as confirmed by industrial users. Examples include:

- Searching for existing parts to be reused as-is or with minor modifications in a new design;
- Searching for existing designs to reuse their simulation/analysis contents in the development of a new product;
- Searching for parts that are similar to a new design in order to reuse/adapt their manufacturing processes; and
- Searching for similar parts to compile comparative data on manufacturing costs and thereby make better estimates.

In many cases, the solution for better product information reuse is not limited to the use of shape-based retrieval tools. As Msaaf et al. [40] point out, the problem must be divided into two steps: (1) a search for similar parts, and (2) an identification of the differences between the retrieved similar parts. The purpose of shape-based retrieval is generally limited to identifying sets of CAD models that can be considered as candidates for product information reuse in numerous scenarios. To determine if two CAD models can be identified as similar in a particular use context **ð** e.g., if the design of an existing similar part can successfully be reused in a new project **ð** a pair-wise comparison of each retrieved candidate model with the original search key is mandatory.

For instance, as prescribed in the Cessna Aircraft Companyõs Supplier Guidelines and Requirements for Engineering Certification Projects [14], a supplier may reuse the qualification data of an approved similar design to support the qualification of a new design submitted to the OEMõs engineering department. This so-called **ò**Qualification by Similarity**ó** procedure, however, requires that **ò**a detailed comparison of the two parts shall be provided that identifies the specific differences and the justification for why the differences meet the requirements of the specification and allow the determination of compliance**ó**.

Furthermore, in the case of manufacturing processesõ reuse, Huang et al. [28] proposed an approach to facilitate the interoperation between new part designs and existing manufacturing processes. Two constructive solid geometry (CSG) models, one defining a partõs geometry in the design space and the other defining the capability envelope set of a parametric machining process, are compared to find their equivalent parameter domains.

2.3 Product Rationalization and Standardization

Product rationalization and standardization can benefit from the use of shape-based retrieval tools such as in developing families of parts and products [66]. Identical parts from separate projects can be located and regrouped to reduce the management and manufacturing costs, particularly by manufacturing in larger batches [40]. Sourcing can also be improved by subcontracting regrouped similar parts to a reduced number of suppliers.

Use of similarity measures like those used in shape-based retrieval have also been reported for low-cardinality comparison in the composition of product families. Viswanathan et al. [65] presented a commonality measure for component pairs within similar product models based on feature-pairõs dimensions and positions. Chowdhury and Siddique [16] then implemented that commonality measure to identify a common platform from 3D CAD models of vacuum cleaners. Accordingly, following the example of product information reuse, product standardization can be considered as a two-step process. After candidate parts or products to be grouped into families have been identified, one further step to this process is to identify and validate the new product familyõs common platform and differentiation enablers through pair-wise comparison.

2.4 CAD Modeling Management

Shape-based retrieval can also be applied in the management of CAD modeling within a manufacturing organization. Msaaf et al. [40] described the use of shape-based retrieval tools in the promotion of modeling best-practices. By locating existing design models similar to a 3D draft, the reuse of best modeling practices ensures continuity in CAD model construction methods. The Parametric Technology Corporation [43] introduced a method for comparing CAD models to prevent model duplication. As new models are stored in the PLM vault, existing models with near-identical shape properties are retrieved and designers alerted as to potential duplication.

2.5 CAD Data Translation/Remastering

A fourth group of 3D CAD model comparison scenarios involves the use of comparison tools to support the geometric validation of translated or remastered 3D CAD models. The objective of the comparison is to verify the geometrical equivalency of two closely related 3D CAD models, i.e. models intended to represent and communicate the same geometric definition of a part.

From the perspective of 3D CAD model comparison, 3D CAD data translation and data remastering can be regarded as the same process. In both cases, a representation of product data, mostly concerning the shape, is fully or partially transferred from a source data format to a target data format, with the possibility for product data degradation during such transfers. They simply differ on how they are executed **ð** translation being automated while remastering is manual **ð** and thus on the sources of degradation/difference between the source and target 3D CAD files. The purpose of the ensuing validation process remains the same: to ensure that the authority data from the source file is accurately accounted for in the target CAD file.

The validation of 3D CAD data translation/remastering by comparing source and target CAD files has become a fundamental procedure in industry when matters of 3D CAD data migration, interoperability or long-term archival arise. Working groups such as AutoSTEP (automotive) [26], LOTAR International (aerospace) [69] and the CAx Implementor Forum (software) [13] have either issued recommendations for best practices regarding geometric validation or developed auditable processes in which 3D CAD data translation validation is key and involve geometric comparison. As a result, provisions for the geometric validation of translated CAD data have been included in recent versions of application protocols AP203 [29] and AP214 [30] of the ISO STEP standard for product data exchange.

2.6 CAx Model Authoring

Another validation process benefiting from 3D model comparison is the validation of downstream 3D CAx models, whose construction often relies on a master 3D CAD model. For example, the modeled geometry of a part in a 3D computer-aided manufacturing (CAM) model has to be equivalent or consistent with the geometry of the originating 3D CAD model, and comparing both models’ geometries constitutes a means to validate the 3D CAM model for use in downstream processes.

Three-dimensional finite-element analysis (FEA) models offer a similar case, in which the initial geometry of a part is regularly simplified for computation purposes. Li and Liu [37] proposed a methodology for abstracting detailed features of a 3D solid model and using dissimilarity metrics between the original model and the computed simplified model to assess the level of simplification. Lockett and Guenov [39] described a similar situation where two similarity measures can be used to evaluate the quality of a mid-surface model – used for the analysis of thin-walled parts – by comparing it to a solid model of the same part.

2.7 Engineering Change Management

The sixth and last application domain for 3D CAD model comparison is engineering change management. As emphasized by 3D CAD model comparison software editors (e.g. [21], [22], [31], [35]) and demonstrated by the research of Chatelain et al. [15] and Al-Sabeh [3], 3D CAD model comparison can be used to identify and document modifications applied to a part or product model between revisions, and by doing so, support the elaboration of engineering change orders (ECO). The impact of a part or product models’ evolution on downstream models, such as process plans, NC programs or simulation models, can thus be determined more accurately and dealt with more efficiently. Likewise, unauthorized engineering changes can be properly detected and managed.

The recognition of a part’s evolution through the comparison of its 3D CAD model’s versions also opens the way to the computer-assisted transposition of shape changes from the definition model to the different downstream CAx models. An example of shape change transposition is the remeshing of FEA models following the modification of the master 3D CAD model’s geometry. François and Cuillière [25] presented a 3D automatic remeshing algorithm based on the preliminary location of geometric modifications between the original mesh and the revised 3D CAD model by means of octree structures. Cuillière et al. [23] and Souaissa et al. [51] presented a similar remeshing algorithm in which the comparison of the two 3D CAD models is performed via the tensor-based matching of boundary representation (B-Rep) entities. Sheffer and Ungor [49] presented a different approach where geometric modifications are expressed in the form of parametric changes between parametric procedural representation of the 3D CAD models. Similarly, Sypkens Smit and Bronsvoort [55], [56] envisioned a way to describe the difference between two models from the point of view of each shape feature to reuse subparts of an original mesh more efficiently. Their approach constructs such a description through the use of cellular representations of the part models to store the persistence qualifications for each feature.

2.8 Synthesis

By organizing the various inventoried use cases for 3D CAD model comparison in six distinct application domains and in close relation with the three identified solution domains, we are able to draw some useful insights:

- As opposed to shape-based retrieval, which has been the focus of numerous research papers and reviews, developments regarding pair-wise 3D CAD model comparison have remained sparse. Even so, several use cases can be identified, and some are complementary to shape-based retrieval initiatives.
- Applications for 3D CAD model comparison in relation to engineering change management require a significant level of detail in terms of the description of 3D CAD model differences; therefore, model difference identification solutions represent a most promising avenue with which to address our concerns about shape change transposition.

For this latter reason, the remainder of this paper focuses primarily on the solution domain of 3D CAD model difference identification (MDI). Accordingly, the next sections describe the specific problem of calculating and representing geometric differences between two 3D CAD models from two other perspectives: the methods used to locate and measure the geometric differences between pairs of 3D CAD models and the tools implementing MDI capabilities.

3 CHARACTERIZING 3D CAD DIFFERENCE CALCULATION METHODS

The problem of determining 3D CAD model differences is intrinsically complex. The overall problem can be separated into three phases [34]:

- *calculation*, a procedure, method or algorithm able to compare two distinct 3D CAD models, i.e. identifying the mappings and, then, the differences between them;
- *representation*, the outcome of the calculation must be represented in some form that is amenable to further manipulations; and
- *visualization*, model differences often need to be presented according to a specific need or scope, highlighting those pieces of information that are relevant only for the prescribed goal.

Calculation and representation are the central ingredients for any pair-wise comparison solution. In this section, we focus on the former aspect by describing and categorizing several difference calculation approaches. As for difference representation, it is highly dependent on the calculation method and, therefore, on the 3D CAD representation scheme used for comparison, as they define the type of data to be represented and manipulated.

3.1 3D CAD Representations Used for Comparison

First, we briefly summarize the different 3D CAD representation schemes that are either implicit to or that can be derived from 3D CAD models. The difference calculation methods presented in this section operate on particular representations of 3D CAD data and are therefore fundamentally affected by their aspects, such as applicability, efficiency and accuracy.

3.1.1 Procedural representation

Most of todayʹs 3D CAD systems implement the feature-based parametric solid modeling paradigm. Modeling operations are stored as features and organized sequentially in a tree, maintaining a parent/child relationship. Creating a model implies instantiating a data structure comparable to a program, and the expected geometry is thereby represented implicitly. Everything related to the development of the model, including 2D sketches, 2D parameters on the sketches, 3D operations and the parameters related to the 3D operations, is recorded. Some edits are done by accessing one of the previous operations and adjusting a sketch or a parameter, while other modifications involve adding, removing, reordering or replacing one or several previous operations. After adjustments have been made, the òprogramó can be replayed to evaluate a different geometric model. However, issues related to the non-uniqueness of modeling sequences in representing solids, as illustrated in Fig. 3, greatly reduce (beforehand) the relevancy of difference calculation methods based on this particular representation scheme (see Table 3) in uses other than those related to version comparison for a given 3D CAD model.

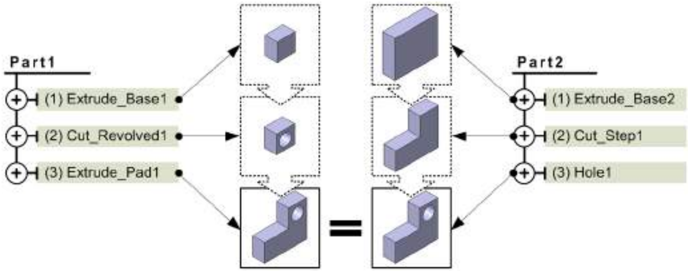


Fig. 3: Non-uniqueness of the procedural representation of solids.

3.1.2 Boundary representation (B-Rep)

Along with the construction history, the parametric feature-based solid modeling paradigm also relies on the boundary representation of solids, more specifically to represent the resulting explicit geometry. The B-Rep data structure stores basic elements composing the boundary of a solid, such as the vertices, the edges, and the faces, with the information about how they are connected. The data in any B-Rep data structure can be classified as either [36]:

- *geometry information*, which generally refers to information about surface equations (faces), curve equations (edges) or point coordinates (vertices); or
- *topology information*, which refers to the interrelationships among faces, edges, and vertices.

3.1.3 Planar facet tessellations

Planar facet tessellations are a specialized type of boundary representation in which points, straight lines and planes are the only geometric entity types allowed for vertices, edges and faces, respectively. Consequently, only point coordinates need to be explicitly specified and stored in the data structure as line and plane equations are computed from neighboring point data. The result is a computationally lightweight representation of 3D shape data broadly used in computer graphics and, thus, for 3D CAD visualization. Digital mock-ups (DMU) typically use this representation scheme for the visualization and the spatial analysis of large assemblies of parts [36].

The evaluation of a planar facet tessellation from a 3D CAD dataset involves the approximation of the explicit modeled shape by means of triangular planar facets. Adjustable parameters regulating the shape approximation, such as the chord tolerance, need to be monitored to ensure a reasonable level of accuracy for the ensuing processes.

3.1.4 Decomposition models

Characterized as auxiliary representations of 3D CAD models, decomposition models approximate 3D shapes by means of their spatial occupancy in the 3D space. For example, voxels are uniformly-sized cubic cells obtained via the 3D rasterization of a given space encompassing a solid. The size of the voxels determines how closely the voxel representation approximates the modeled solid.

Since the memory space required to store the voxel representation increases dramatically as the size of the voxels decreases, one may opt instead for the octree representation. An octree representation is similar to a voxel representation in that it represents a solid as an aggregate of hexahedra, but it reduces the memory requirement considerably by dividing the space differently and representing it in a navigable tree-like data structure. Cellular representation is also a method of representing a solid as an aggregate of simple cells. However, it does not impose a strict restriction on the allowable shape of the cells to be used [36].

3.2 Geometric Comparison

3.2.1 Global geometric properties

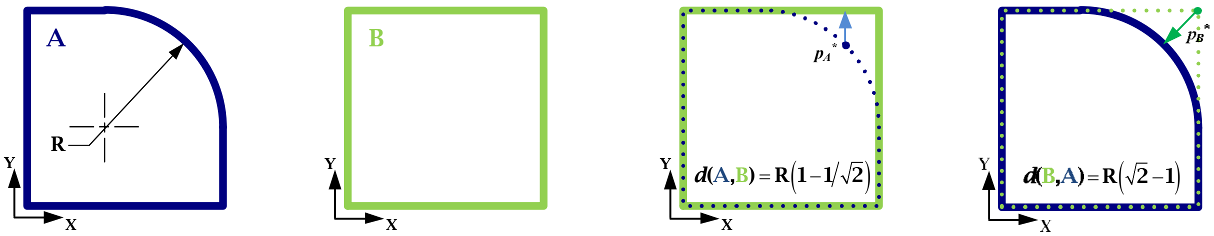
The comparison of global geometric properties such as 3D CAD models’ volumes, surface areas, moments of inertia, etc., allows for the quick and straightforward validation of two models’ geometric equivalency. For such metrics, tolerances are required in order to establish a threshold on the acceptable difference expressed in percentages between the compared models. However, no information on the nature and locus of the differences between the compared shapes can be provided, nor do the differences offer much significance in terms of functional part features, such as measuring the distance between two faces, for example.

Only results with a low level of details (yes-no, rating) can therefore be achieved using this particular approach. However, the very low computation cost of these difference calculation algorithms enables their use in scenarios such as detecting duplicate 3D CAD models in large PLM vaults [43]. Also, global geometric properties are being implemented as “Geometric Validation Properties” (GVP) [13] in application protocols AP203 [29] and AP214 [30] of the ISO STEP standard for product data exchange.

3.2.2 Point-to-part deviation

Also called the “Cloud Of PointS” (COPS) mechanism [13], the point-to-part difference calculation method is based on the evaluation of the *Hausdorff metric* [4] which, fundamentally, measures how far two subsets of a metric space are from each other. The surface of the first 3D CAD model is discretized by a set of sampling points. For each sampling point, a deviation is calculated as the smallest distance separating it from the surface of the second 3D CAD model. The highest deviation from all sampling points denotes the *forward Hausdorff distance*. The *backward Hausdorff distance* is calculated the same way, i.e. with the sampling points lying on the surface of the second 3D CAD model, since both distances will not always equate ($d(A,B) \neq d(B,A)$), as demonstrated in two dimensions by Fig. 4. The highest value between the two directed Hausdorff distances determines the Hausdorff metric; accordingly, the corresponding sampling point identifies the locus of the global maximal deviation on the models’ surfaces.

The sampling domains, i.e. the 3D CAD model surfaces, may be partitioned into a number of smaller subdomains prior to the distance computation to enable the location of multiple local deviation maxima on the models’ surfaces. Typically, face entities from a B-Rep data structure are used as sampling subdomains [21], [31]. Heuristics may also be used to distinguish several local deviation maxima and their neighboring regions among the sampling points after the distance computations [67].



(a) (b) (c) (d)

Fig. 4: Illustrating the Hausdorff metric calculated between two partsî boundaries (in 2D): (a) Part A with a round feature, (b) Part B with sharp corners, (c) Forward Hausdorff distance calculated between sampling points from the boundary of part A and the boundary of part B, (d) Backward Hausdorff distance calculated between sampling points from the boundary of part B and the boundary of part A.

A tolerance must be applied to the calculated deviations in order to identify the point-to-part deviations sizeable enough to be considered as relevant geometric differences. Color scales are frequently used for the visualization of point-to-part deviation results on the surface of the modeled 3D shapes [10], [22], following the example of point-cloud-based inspection software tools [44]. Point-to-part deviation calculation is typically a pair-wise comparison method, as distance computation is computationally expensive, and one of the few capable of measuring multiple differences.

Rapid distance computation constitutes a problem on its own, as taken up by the related research field of computational geometry. When transposed in a 3D CAD setting, some proposed distance computation solutions introduce novel uses for decomposition models. For example, Tsai [63] presents two rapid and simple algorithms for approximating the distance function for given isolated points on uniform grids that can be derived from voxel representations. Also, Pottman et al. [45] propose the d^2-tree, an octree data structure which stores, in each of its cells, a local quadratic approximant of the squared-distance function of a geometric object. Bearing in mind that these distance computation algorithms yield approximate results, their respective use in an MDI context requires the complementary use of refining algorithms.

3.2.3 Spatial occupancy comparison

As 3D CAD models fundamentally embody the definition of 3D geometric shapes, i.e. subsets of the 3D Euclidean space, some difference calculation methods focus on spatial occupancy. The calculation of the regularized Boolean operations from set theory between the two modeled solids constitutes another approach to compare two 3D CAD models. Given two subsets A and B representing the modeled solids from the reference and target 3D CAD models, respectively, the corresponding difference calculation methods essentially aim at evaluating the three mutually exclusive subsets given by the regularized difference operations (A **ð*** B) and (B **ð*** A), and by the regularized intersection operation (A ž * B), as pictured in the Venn diagram of Fig. 5. In the context of mechanical CAD model comparison, these three subsets symbolize regions of material removal, material addition (with respect to the reference part), and material common to the two parts, respectively. Accordingly, spatial occupancy comparison is typically used to mainly locate and visualize differences.

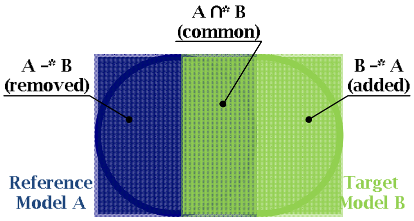


Fig. 5: Illustration of the calculation of regularized Boolean operations for comparing 3D CAD models.

Most 3D CAD systems implement a geometric modeling kernel which includes the basic Boolean operations that perform the regularized union, intersection and difference of 3D objects. These operators may either be used as-is or through automation to compare the volumes of two modeled parts and identify regions of material removal, material addition and common material.

Dassault Systèmes SolidWorks® [50] provides an automated implementation of such a calculation method. The outcome of the operation is three sets of editable solids, each resulting from the calculation of either of the two directed set differences or of the set intersection of the two input solids. The robustness of this method is directly related to the modeling kernel's robustness in the calculation of set operations for compared solids displaying issue-prone features like coincident boundaries or boundaries intersecting at vanishing angles, which are commonly encountered between similar parts.

The use of auxiliary representations, such as decomposition models, to obtain the result of regularized Boolean operations on two solids can increase computational efficiency. For example, representing both solids simultaneously by means of voxels enables the calculation of the Boolean operations on the integer values of 1 (overlapping solid) or 0 (empty) for the corresponding voxels of the two solids [12], [25].

The superposition of 3D shapes constitutes a faster and more straightforward approach to locate regions of material removal, material addition and common material between two similar 3D CAD models. DMU analysis tools usually implement 3D shape superposition to compare parts, since the corresponding algorithms are similar to those used to verify part mating and clearance and detect part interference in assemblies. Different colors are used to identify common intersecting and differentiating regions on the modeled parts, as shown in Fig. 6. Examples of software tools that implement the superposition approach are CATIA® V5 [12] and some 3D CAD visualization tools such as Oracle AutoVue® [7], Lattice Technology XVL Studio® [67] and Actify SpinFire™ [53].

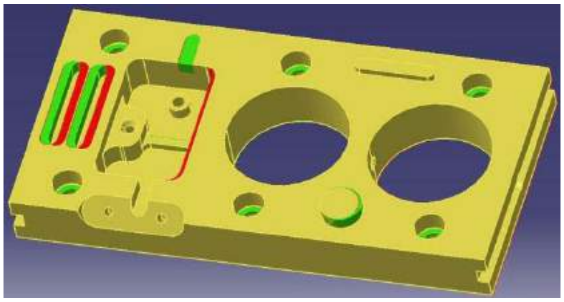


Fig. 6: Superposition of 3D shapes using CATIA® V5 *DMU Space Analysis* workbench [12].

3.3 Data Structure Matching and Comparison

A second 3D CAD difference calculation approach consists of comparing 3D CAD models by means of their implicit data structures. Data structure matching and comparison distinguishes itself from geometric comparison since it fundamentally processes representation data structures instead of computed geometric results. Any CAD representation scheme can be the subject of this type of matching algorithm: CSG (e.g. [15]), B-Rep (e.g. [20]), parametric feature-based (e.g. [48]), cellular representation (e.g. [55]), etc.

For example, comparing two 3D CAD models͛ procedural representations or òprogramsó, will locate differences in the nature, the quantity and the order of the operations used to build the models, along with the differences at the operations͛ parametric level. Difference calculation between B-Rep data structures of two 3D CAD models essentially involves the matching of boundary entities with regard to their respective explicit geometry and/or topological information. Entities are then classified according to their own and their neighboring entities͛ matching status as per specified criteria. For instance, a pair of matched faces having the same surface equation but different boundary edges may be classified as òrelimitedó or òaffectedó faces.

The most intricate part of the calculation task is the matching, or mapping, of specific model elements. Following the example of model matching approaches used in Model-Driven Software Engineering (MDSE) [34], four matching approaches for 3D CAD data structures have been identified.

3.3.1 Static identity-based matching

Assuming that each model element has a persistent and unique identifier that is assigned to it upon creation, matching model elements are identified based on their corresponding identities. This approach must involve 3D CAD models that were constructed dependently of each other for persistent identifier to be available in both models. Also, it cannot be applied to 3D CAD formats that do not support maintenance of persistent unique identifiers.

PTC͛s Pro/ENGINEER® [48] offers MDI functionalities for comparing proprietary procedural models which perform static identity-based matching of modeling operations and parameters. Al-Sabeh [3] presents a similar algorithm using persistent identifiers of modeling features only for the comparison of CATIA V5 [12] part models. Sypkens Smit and Bronsvoort [55] exploit the mapping of persistent features between two versions of a feature model. The cellular representation of the feature models enables them to compare each feature pair͛s spatial occupancy independently from their interaction with other features.

3.3.2 Signature-based matching

The identity of each model element on which their true/false matching relies on is no longer static; rather, it is a signature assembled from the values of its attributes and properties, or calculated dynamically by means of a pre-defined function. For 3D CAD model elements, geometric data may be used to calculate the signature just as much as descriptive data (e.g. names of feature instances). Signature-based matching can therefore be used to compare isolated models, but first, a series of functions to create the signatures of different types of model elements needs to be specified.

One of Dassault Systèmes͛ SolidWorks® [50] available comparison functions uses the signature-based approach, matching modeling operations between two construction histories by their (editable) names. The *3DComparator* tool described by Msaaf et al. [40] extracts geometric signatures for faces and matches them to distinguish equivalent faces from different faces between two B-Rep models.

3.3.3 Similarity-based matching

As opposed to treating the problem of model matching as true/false identity, the 3D CAD modelsõ data structures are treated as typed attributed graphs and matching elements are identified based on the aggregated similarity of their attributes and geometric properties. As not all characteristics of model elements are equally important for model matching, similarity-based algorithms typically need to be provided with relative weights for each characteristic, and thus, must often undergo an empirical trial and error fine-tuning process.

For example, Cuillière et al. [23] and Souaissa et al. [51] presented a model comparison algorithm that computes the metric tensor, inertia tensor and barycenter of each faceõs and each edgeõs respective set of control points from two NURBS-based B-Rep models. Faces and edges from the two models are then matched gradually by verifying the equivalency of their computed properties in a particular order **ð** which equates to giving each property a different weight in the overall similarity measure function. Chatelain et al. [15] proceed likewise to compare CSG models. Primitive solids are characterized by their type, transformation matrix, dimensional parameters and position index in the CSG tree, respectively. Then, they are recurrently matched between models with respect to reducing subsets of the characteristics, resulting in decreasing degrees of similarity between matched primitive solids.

3.3.4 Syntax-specific matching

Syntax-specific matching algorithms incorporate the semantics of the target 3D CAD representation scheme or format, thereby providing more accurate results and also drastically reducing the search space. For example, in comparing B-Rep data structures, Pan et al. [42] incorporate the knowledge that it only makes sense to compare two edges if the faces they are adjacent to are already known to match; thus reducing the number of model element comparisons that need to be performed. Similarly, PTCõs CoCreate® Modeling [19], [20] implements a B-Rep difference calculation algorithm in which vertex, edge and face mappings are computed progressively using geometric attributes and the mappings from lower-order topological entities simultaneously **ð** i.e. edges are matched using vertex mappings and faces are matched using edge mappings. Accordingly, the syntax-specific matching approach not only exploits intrinsic characteristics of model elements as compared to the previous three approaches, but also uses specific information on how they relate to other model elements in their respective data structure.

3.4 Pose Registration

All of the difference calculation approaches described here require that the shapes being compared are positioned and oriented consistently in their respective coordinate systems beforehand; that is, they have to fit appropriately on top of each other. In any given pair-wise comparison scenario, this preliminary step, referred to as *pose registration* [68], may either be executed automatically or manually since it only needs to be executed once before pair-wise model comparisons, as opposed to shape-based retrieval (1-to-N) problems. Many methods for the automatic pose registration of explicit geometric models are available (e.g. [46], [58]); a popular one being the principle component analysis (PCA) transformation [68].

Remarkably, a few difference calculation algorithms manage to implicitly perform the pose registration of the compared models. The algorithms proposed by Msaaf et al. [40] via their 3DComparator, and by Cuillière et al. [23] and Souaissa et al. [51], notably, use pose-independent geometric signatures to match B-Rep entities. Consequently, pose registration is performed as part of the algorithms by using the mappings determined by their respective matching sub-algorithms.

3.5 About Comparing B-Rep Models

Using B-Rep difference calculation methods will benefit to some comparison scenarios in which ensuring the topological equivalency of 3D CAD models’ boundary representations becomes critical. For instance, information about a surface to be machined and its boundary edges is necessary for the calculation of NC tool paths. If the topological structure of a reference 3D CAD model was to be altered in some way, such as via 3D CAD data translation as shown in Fig. 7, the ensuing NC toolpaths’ calculation process may produce detrimental results, such as excessively longer machining times, or even fail.

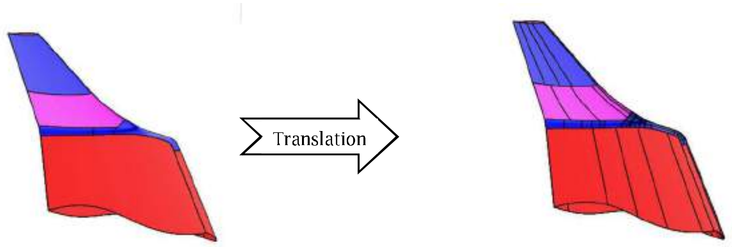


Fig. 7: Examples of two geometrically equivalent yet topologically different 3D CAD models of a wingtip: (a) Source model composed of ten faces, (b) Target model composed of over a hundred faces. (Courtesy of CapVidia®)

3.6 Relevance in a MDI Problem

As described in Section 2, MDI problems comprise the pair-wise comparison of two 3D CAD models and require a significant level of detail regarding the calculation and representation of the differences. Appropriate difference calculation approaches are bound to provide enough information leading at least to the distinction of each single difference within the parts’ geometric definitions. Methods using global geometric properties should therefore be dismissed. Moreover, the trade-off between the accuracy of the calculated results and the computational efficiency of the difference calculation, specifically identified in approaches using auxiliary approximate geometric representations, may lose its bearing. MDI solutions can focus primarily, but not exclusively, on the accurate calculation and representation of the differences, which is their basic function, rather than on the computational efficiency of an algorithm executed singly.

4 INVENTORING THE CURRENT MDI-CAPABLE SOFTWARE TOOLS

In order to go deeper into the description of the state of the art about 3D CAD model difference identification (MDI), this next section reports on the variety of existing software tools capable of locating and detailing geometric similarities and/or differences between two given 3D CAD models. Aside from their sought-after functionalities, tools were identified and inventoried based on their availability to the general public. Consequently, commercially available software tools make up the entirety of the compiled inventory, as no publically-available instance of other types of implementations, such as research prototypes, were found. Still, this particular review contributes to our purpose as no comprehensive inventory of MDI tools had been made to date. For some examples of shape-based retrieval software, the reader may refer to [40].

The following inventory was divided into four categories based on the software tools’ primary function: (1) 3D CAD systems, (2) 3D CAD validation tools, (3) 3D CAD visualization and collaboration tools and (4) other miscellaneous tools with MDI capabilities. This categorization allows us to distinguish some issues that are characteristic of the MDI problem.

4.1 3D CAD Systems

MDI capabilities are usually available in 3D CAD systems amongst many others peripheral model analysis functionalities. Table 3 lists and describes seven (7) different CAD systems comprising such capabilities.

According to their respective documentation, the 3D CAD systems’ main purpose in providing pair-wise model comparison capabilities is to allow users to compare successive versions of a model and, ultimately, to manage change in 3D CAD models. Notably, 3D CAD systems are the only software tools that allow the comparison of the models’ procedural representations, i.e. the sequence of modeling operations and their corresponding parameters (also referred to as feature trees, specification trees, construction or modeling histories, etc.), provided that the compared models are both proprietary models. The comparison of imported models is also possible, but is heavily dependent on the 3D CAD system’s importation capabilities, which are likely to induce some level of data degradation during the translation process (e.g. loss of modeling features, topological alterations, etc.).

3D CAD system	*Ref.*	*Comparison object*		*Additional details*
		Explicit geometry	*Procedural representation*	
CATIA® V5	[12]	X		From *DMU Space Analysis* workbench.
SolidWorks®	[50]	X	X	Available in the *SolidWorks Utilities* add-in; Developed in part by Geometric Ltd [27].
NX®	[41]	X	X	
Pro/ENGINEER®	[48]	X	X	
CoCreate®	[19]	X		Proprietary method described in [20].
SpaceClaim®	[52]	X		
TopSolid®	[60]	X		

Tab. 3: 3D CAD systems with MDI capabilities.

4.2 3D CAD Validation Tools

The second category comprises current, commercially available MDI-capable software tools that support the geometric validation process of 3D CAD data translation/remastering. Although initially designed for geometric validation applications, all of the inventoried validation tools can be used as MDI tools, as they provide an applicable level of detail about the located differences in those cases where the validation fails. All but one of the tools listed in Table 4 are integrated in 3D CAD feature-based translation software.

Editor	*Software tool*	*Ref.*	*Interoperability mode*	*Additional details*

CapVidia	CompareVidia®	[21]	Licensed libraries	
CT CoreTechnologie	3D_Evolution©	[22]	Licensed libraries	
Elysium	CADdoctor®	[24]	Licensed libraries	
ITI TranscenData	CADIQ®	[31]	CAD systems’ API	
Kubotek	Kubotek Validation Tool™	[35]	Licensed libraries	
Theorem Solutions	Theorem Process Manager© (TPM)	[59]	Licensed libraries	
Translation Technologies	Mirror Model Comparator© (MMC)	[61]	CAD systems’ API	Proprietary method described in [62].

Tab. 4: 3D CAD validation software tools with MDI capabilities.

As validation tools, the key result these software tools are primarily designed to provide is a straightforward pass/fail diagnosis regarding the compared models’ explicit geometric equivalency. The compared models’ equivalency is usually based on selectable and/or adjustable criteria. When these criteria are not completely fulfilled, the validation tools may indicate where these discrepancies are located in relation to the pre-set criteria.

The 3D CAD data translation/remastering process these tools are designed to validate inevitably requires them to compare 3D CAD models represented in heterogeneous formats. Two opposite approaches to this interoperability issue can be identified. First, a validation tool may use licensed libraries from the major 3D geometric kernel editors to read native files and import the data into its own 3D geometric kernel. Such an approach benefits the comparison process, as the validation tool does not require CAD systems to be installed on the computer. However, it does involve the translation of the native data, which may induce some undesirable degradation unmanaged by the comparison tool.

Alternatively, a validation tool may use a 3D CAD system’s application programming interfaces (API) to analyze the native data as it was originally represented. While the risk of data degradation due to the translation process is minimized, this second approach requires the two compared models’ source 3D CAD systems to be installed and their respective API’s to be made available in order for the comparison to take place.

4.3 3D CAD Visualization and Collaboration Tools

As a key part of PLM, 3D CAD visualization and collaboration tools are designed to enable the viewing, manipulation, annotation and sharing of engineering 3D models throughout the different functions of an extended enterprise, without resorting to the native 3D CAD systems. Some of those tools, as listed in Table 5, offer MDI capabilities as an analysis function that can support, among others, the dissemination of engineering change applied to part models.

On the matter of 3D CAD interoperability, visualization tools purposely resort to licensed libraries to read native files in order to circumvent the use of source 3D CAD systems. Accordingly, degradation of native data is predictable as collaboration tools commonly exploit lightweight 3D geometric formats to facilitate 3D CAD data sharing, such as on the web [64]. For example, none of the tools listed in Table 5 preserves the procedural representation, i.e. features and parameters, of geometric data imported from native files. Furthermore, lightweight formats commonly approximate exact geometry with planar facet tessellations, raising issues regarding the accuracy of the difference calculation process between explicit geometries.

Editor	*Software tool*	*Ref.*	*Additional details*
Actify	SpinFire™	[53]	
Adobe Systems	Acrobat® Pro	[2]	Available in *3D Reviewer*©.
C4W	3D Shop ModelScan©	[1]	
CADCAM-E.com	EnSuite©	[10]	
Lattice Technology	XVL Studio© Professional	[67]	
Oracle	AutoVue© Electro-Mechanical Professional	[7]	
Synergis Software	Adept©	[54]	MDI capabilities provided by [7].

Tab. 5: 3D CAD visualization and collaboration software tools with MDI capabilities.

4.4 Other Software

When it comes to inventorying existing software tools, the sought-after 3D CAD MDI capabilities may not be explicitly detailed as one of the software's key features or labeled functions, but rather be deducible with some ingenuity. A broader view of the state of the art is thus possible. Nevertheless, it must be kept in mind that these implicit capabilities might inevitably be restricted in their use since they may not have been initially designed for the specific purpose of MDI.

Point-cloud-based inspection software tools, such as InnovMetric Software's PolyWorks® [44], constitute a first type of software that can be used to compare 3D CAD models. An automated inspection system such as the one described by Prieto et al. [47] will take in an unordered cloud of the 3D points of an actual part obtained from a high-resolution 3D range sensor, along with its 3D CAD model. The cloud is then segmented by computing the minimal distance and comparing some local geometric properties between the 3D points and the CAD model's surface.

Then again, two 3D CAD models can be compared by substituting the point cloud obtained from the 3D range sensor with a point cloud obtained from the surface of another similar 3D CAD model by means of macro programming. Such practice basically reproduces a variant of the point-to-part method for calculating geometric differences, which is detailed in section 3.

Autodesk® released a technology preview of Autodesk® Inventor® Fusion [5], a history-free CAD modeling software. When used concurrently with the parametric feature-based CAD software Autodesk® Inventor® [6], this technology preview includes a complementary module called the Inventor® Fusion Change Manager. The module is designed to propagate direct-modeling modifications applied to a 3D CAD model in a history-free environment to a feature-based parameterized version of the same model in a history-based environment. The propagation process begins with the comparison of the new history-free version with the earlier feature-based version of the CAD model in order to locate the modifications and compute their representation as new parameterized feature instances. At this prototype stage, the comparison capabilities of the Change Manager module are strictly limited to successive versions of Inventor® 3D CAD models, the newer version having been edited in Inventor® Fusion.

5 PERSPECTIVES

By describing and analyzing the uses, the tools and the methods related to the comparison of 3D CAD models, this paper allows us to outline the research perspectives into this promising CAD- and PLM-related domain; more specifically, in relation to the MDI-related problem of shape change transposition. The process of transposing shape change between 3D CAD models may be divided into two fundamental steps (see Fig. 1): (1) the location and measurement of geometric differences between a modified reference model and an initial target model, each formatted differently yet related (e.g. the initial target model embodies an earlier version of the part modeled by the modified reference model) and (2) the modification of the initial target model based on an adapted representation of these geometric differences. We describe three research perspectives we intend to pursue in future work.

5.1 Difference Representation

Our survey of 3D CAD model difference calculation approaches and methods was key to this paper, as it outlines one of the central ingredients for any MDI solution, the other component being difference representation. Whereas a number of difference calculation methods and algorithms could be reported on and categorized, developments regarding difference representation have remained of secondary importance. The representation of such differences is highly dependent on their calculation. However, the requirements regarding what information must be provided by the comparison influence the selection of the proper calculation method.

In the context of shape change transposition, the intended update of the target model determines the outcome of the geometric difference calculation step which is to be represented in some form that is amenable to further manipulations, whether they are to be performed manually or automatically. New emphasis should therefore be put on the adequate representation of 3D CAD model geometric differences, such as outlining the minimal set of requirements that should be taken into account in order to define a suitable representation technique for the problem at hand.

5.2 Search for Representation Completeness

Due to their higher level of semantics, the comparison of the 3D CAD modelsʼ feature-based procedural representations is expected to provide more relevant information on geometric differences from the point of view of design engineering than the other difference calculation and representation approaches. However, this particular approach inherently lacks flexibility, being strictly limited to the comparison of 3D CAD models directly derived from one to another. Also, since the compared shapes are represented implicitly, adequate calculation precision and recall for explicit geometric differences cannot be guaranteed.

A promising avenue for an MDI solution to efficiently support the scenario of shape change transposition would be to develop a difference calculation and representation approach that combines the calculation precision and recall of explicit geometry comparison with the representation completeness of procedural representation comparison. One key challenge of such an avenue would reside in overcoming the issue of comparing heterogeneously-represented 3D CAD models.

5.3 Parametric Representation of Geometric Differences

Intuitively, dimensions and other geometric constraints, referred to here as parametric data, fundamentally constitute the first level of engineering semantics that distinguish a 3D CAD model embodying the geometric definition of a mechanical part from any given 3D shape model. Systematically represented in both the feature-based parametric and the direct (explicit) solid modeling paradigms implemented by most modern 3D CAD systems, parametric data can also be seen as the primary object of engineering change applied to the geometric definition of a part.

Unfortunately, despite the variety of MDI tools and difference calculation approaches surveyed in this paper, very few developments have been aimed at representing 3D CAD geometric differences via their parametric representation. The comparison of procedural representations involves locating parametric differences between matched modeling operations, even though such parametric data remains implicit with respect to the geometry. Whether it is through difference calculation, difference representation or some combination of the two, the objective is to work towards an MDI solution for shape change transposition that takes advantage of the compared 3D CAD modelsʼ parametric representation of engineering data.

6 CONCLUSION

This paper reviewed recent developments in the domain of 3D CAD model comparison. The subject was outlined, in a comprehensive approach, from three related points of view, providing the groundwork for our projects addressing the problem of shape change transposition. First, we described and analyzed the possible uses for 3D CAD comparison and identified 3D CAD model difference identification (MDI) as the most promising solution domain. Existing MDI-capable software tools were inventoried and categorized. A survey of various difference calculation methods was also presented. Finally, in light of the review, research perspectives towards innovative MDI methods in shape change transposition scenarios were then contemplated.

Our research clearly shows that pair-comparison of 3D CAD models does not draw as much attention in the CAD and PLM research communities as shape-based retrieval. By concurrently reporting on the scenarios, the tools and methods for 3D CAD model comparison, the goal is to highlight the potential of these tools to address the contemporary challenges of PLM and, thus, bolster new developments in the comparison of 3D CAD models. Moreover, as software developments have been made in recent years, comparing available solutions constitutes a complex and delicate task that remains to be performed.

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