3D CAD Model Comparison: An Evaluation of Model Difference Identification Technologies

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ABSTRACT

The use of 3D CAD in mechanical product design has become a standard practice. Consequently, methods and tools are continually being developed to improve designers' efficiency in the creation, modification and analysis of 3D CAD models. Recent software developments had led to the emergence of multiple tools capable of comparing 3D CAD models to locate shape similarities or differences, leading to benefits in various CAD- and PLM-related application domains such as design reuse, data exchange and engineering change management. This paper describes evaluation trials that were performed on sets of commercially available 3D CAD model comparison tools. The goal was to evaluate their capacity to efficiently calculate, represent and display 3D CAD model differences in shape change transposition scenarios where shape modifications must be precisely located and elaborated in order to be consistently propagated between application-specific models of a product. First, some basic concepts of 3D CAD model comparison are presented. Then, simulated shape change assessment scenarios are defined to pilot two series of evaluation trials intended for existing software tools capable of comparing 3D CAD procedural and explicit models, respectively. The results are summarized and conclusions are drawn.

Keywords: model comparison, software evaluation, difference identification.
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1 INTRODUCTION

The development of complex products depends on engineering processes through which a product's definition evolves systematically, driven by the concurrent work of many specialists from distributed teams producing and modifying the product model, making decisions and taking actions accordingly. In numerous cases, those decisions and actions highly depend on the proper identification,

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representation and integration of what differentiates the new version of the product model from its previous versions. Accordingly, innovative methods and tools are sought after to enable the fast, accurate and comprehensive identification and representation of the differences between models.

Three-dimensional (3D) CAD model comparison has been the focus of several advancements in the last decade, notably as part of product lifecycle management (PLM) initiatives towards better product information reuse [6], [20] and product data exchange [8]. Recent commercial software developments focused on the pair-wise comparison of 3D CAD models, mostly enabling the detection of model differences for validation purposes [5]. The relevance of such comparison tools in engineering change management scenarios remains however to be demonstrated, as few were expressly designed for the detailed assessment and representation of shape changes between versions of a mechanical part.

This paper falls within the framework of a research project addressing the subject of product *shape change transposition* between heterogeneously formatted 3D CAD models. The objective is to develop a novel 3D CAD model comparison mechanism providing application-specific representations of shape differences between models of an evolving mechanical part, thus optimizing their identification, their interpretation and their integration by the individual engineering processes responsible for updating target application-specific models.

Figure 1 illustrates a sample case of shape change transposition. An initial reference model, released by Design Engineering in the form of a STEP file, 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). Eventually, 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 the description of this shape change in the manufacturing domain.

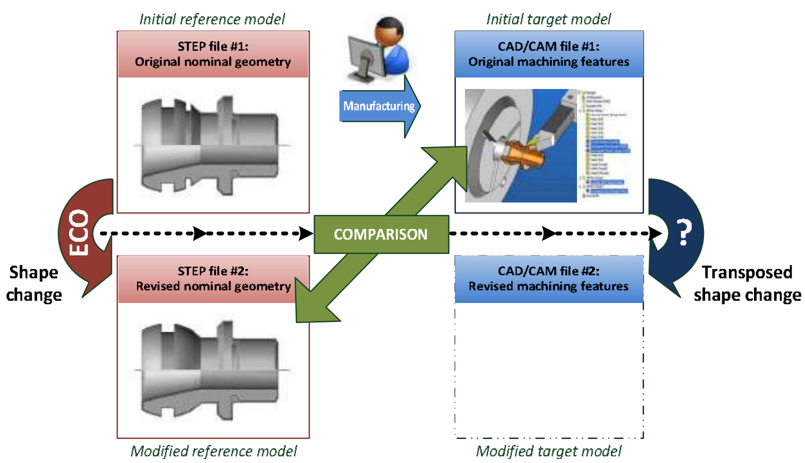

Fig. 1: Sample case of shape change transposition: Modifying a CAD/CAM model based on revised geometry.

A preceding paper by the same authors [5] identified and organized existing literature and recent developments relating to 3D CAD model comparison, including an inventory of commercially available comparison software tools. While such review focused mainly on the applicative and theoretical

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aspects of 3D CAD model comparison, this paper explores its practical aspect by describing two series of evaluation trials that were performed on a representative sampling of commercially available comparison software tools. The objective of the evaluation trials was to assess if and how much these specific tools, implementing the various difference calculation methods reported previously, could effectively contribute to the transposition of a shape change between application–specific models that must be kept consistent. Results of this investigation would then set the groundwork for the development of a novel 3D CAD model comparison mechanism.

The structure of this paper is as follows. Section 2 summarizes some of the theoretical aspects of 3D CAD model comparison that were introduced in [5] and are relevant to the current investigation, such as the basic functions and solution domains, the composition of the model comparison problem and an overview of current difference calculation methods. In Section 3, we give a brief description of our approach in devising and performing the evaluation trials, including the definition of the set of criteria that were used to evaluate the software tools' relevance in two simulated shape change assessment scenarios. Sections 4–5 detail the first and second series of evaluation trials on software tools performing 3D CAD model comparison via the models' procedural and explicit geometric representations, respectively, along with results and other observations. Conclusions and future contributions are described in Section 6.

2 AN OVERVIEW OF 3D CAD MODEL COMPARISON

Prior to the evaluation trials, this first section briefly describes the topic of 3D CAD model comparison as it is exposed in current CAD– and PLM–related documentation and research literature. We refer to 3D CAD model comparison as the general process of comparing two or more CAD models in order to yield a statement or an estimate of their geometric similarities and/or differences and, consequently, to support decision making in any given product lifecycle phase. For a more detailed review on this specific topic, the interested reader can refer to a previous work by the same authors in Ref. [5].

2.1 Application and Solution Domains

Six (6) 3D CAD model comparison application domains were identified to categorize the numerous and varied use cases for comparison during the different phases of the product lifecycle:

- *Product information reuse* – achieving one of PLM's key aspects towards reducing costs and delays, by using a product's shape to retrieve and assess reusable product data such as manufacturing processes [16], sourcing and pricing information [24], qualification tests results [9], etc.;
- *Product rationalization and standardization* – eliminating duplicates and grouping similar existing parts and products into new families [10] or optimized manufacturing batches for more efficient outsourcing [24];
- *CAD modeling management* – preventing model duplication and promoting modeling best–practices on the basis of geometric comparison between existing and new 3D CAD models [26].
- *CAD data translation and remastering* – monitoring the possible lost or degradation of 3D CAD shape data rendered automatically (translation) or manually (remastering) in formats different than the one it originates from (e.g. [8]);
- *CAx models authoring* – verifying the geometric consistency of intermediate or analysis models with respect to the master model they are derived from (e.g. [23]); and
- *Engineering change management* – identifying and assessing the impact of ordered shape changes on a part's definition and downstream models, such as process plans, NC programs,

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analysis and simulation models (e.g. [32], [35]). Shape change transposition cases, like the one pictured in Fig. 1, belong to this particular application domain.

Current 3D CAD model comparison solutions cannot contribute interchangeably to any application domains. Depending on the use case, the basic function of the comparison process varies with regard to two key factors which are the comparison's *cardinality* – comparing two (1:1) or many models (1:N) – and the *level of details* expected from the comparison – ranging from a simple "Yes–No" diagnosis to elaborated descriptions of the differences. Accordingly, as pictured in Fig. 2, three distinct solution domains were identified to categorize 3D CAD model comparison solutions implementing similar basic functions.

Shape-based retrieval collates model comparison solutions implementing basic functions such as "finding duplicate" or "finding similar" models. These solutions usually relate to use cases from the *product information reuse* and *product rationalization and standardization* application domains where large sets of models are compared (1:N cardinality) and where simple results are expected (finite sets of equivalent models or scale–based distributions of similar models). Examples of shape–based retrieval solutions were largely reviewed in many previous works (e.g. [6], [19]). Higher cardinalities require higher computational efficiency, leading a vast majority of shape–based retrieval solutions to use lightweight pre–computed shape signatures to aggregate shape and other model features for fast, yet coarse comparison.

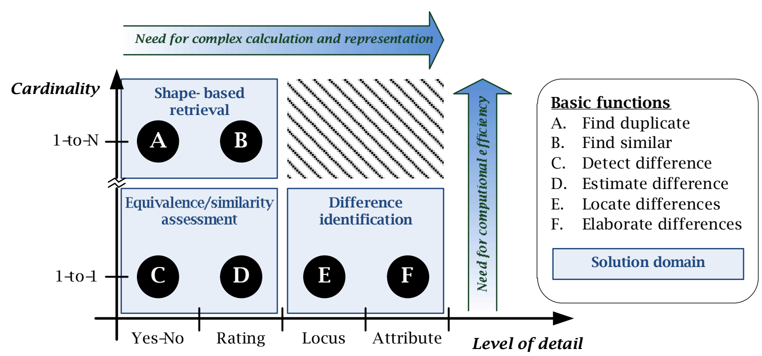

Fig. 2: Solution domains and basic functions as a relation between the required level of detail and cardinality.

The *equivalence/similarity assessment* solution domain comprises model comparison solutions implementing the "detect difference" and "estimate difference" basic functions. These solutions are used to check if two models (1:1 cardinality) are equivalent according to some explicit criteria or to estimate their relative similarity, i.e. providing a qualitative appraisal of how close or different they are from each other (few to no details about the similarities/differences). Application domains such as *CAD data translation/remastering* (e.g. [8]) and *CAx models authoring* (e.g. [23]) benefit mainly from equivalence/similarity assessment solutions.

Then, *model difference identification* (MDI) constitutes the third solution domain, organizing model comparison solutions implementing basic functions such as "locating differences" and "elaborating differences" between pairs (1:1) of 3D CAD models. As high levels of details are required in use cases such as those from the *product information reuse*, the *product rationalization and standardization* and the *engineering change management* application domains, MDI solutions involve

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complex mechanisms for the calculation and the representation of model differences (e.g. [12]). Accordingly, their use is better suited for low–cardinality or *pair-wise* model comparison problems.

This paper focuses on pair–wise model comparison solutions, most specifically on MDI solutions, as they can be applied to *engineering change management* use cases, such as the transposition of shape changes between two models. Consequently, shape–based retrieval and equivalence/similarity assessment solutions are considered out of scope in the present work.

2.2 Components of Model Difference Identification

The process of identifying similarities and differences between two 3D CAD models is intrinsically complex. The model difference identification process can be separated into three major components [22]:

- *Calculation* – a procedure, method or algorithm able to compare two distinct 3D CAD models, i.e. identifying mappings between model elements and, then, similarities and differences;
- *Representation* - the outcome of the calculation must be described and represented in some form that is amenable to further analysis or 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 MDI comparison solution, but all three components tend to overlap. Difference representation is highly dependent on the calculation method and, therefore, on the representation of CAD data used for comparison, as they define the type of data to be represented and manipulated. Therefore, the effectiveness of difference representation is often compromised by factors such as the calculation method or the scope of the difference. As for visualization, it is realized by specifying a concrete syntax which renders the abstract representation of differences. Accordingly, in some solutions, both the representation and the visualization of model difference are rendered with the same notation (e.g. model comparison by means of graphical representations).

2.3 Difference Calculation Methods

Two approaches for calculating 3D CAD model differences between pairs of models have been identified among current model difference calculation methods: (1) explicit geometric comparison and (2) model data structure matching and comparison. Explicit geometric comparison operates on the explicit representation of geometric objects, like solids, surfaces or point sets, for which geometric properties can be evaluated, e.g. volume, area, distances, positions, etc. Conversely, model data structure matching and comparison operates on CAD data structures, model data elements, like B–Rep entities or modeling operations, and their attributes.

Generally, whatever the difference calculation method, compared shapes must be positioned and oriented consistently in their respective coordinate systems beforehand; that is, they have to fit appropriately on top of each other in 3D space. Such preliminary operation is known as *pose registration* [38]. Some particular algorithms are able to perform pose registration implicitly by manipulating pose–independent geometric properties (e.g. [24], [32]).

Examples of explicit geometric comparison methods are the comparison of global geometric properties, the point–to–part deviation calculation and the spatial occupancy comparison. The comparison of global geometric properties such as the 3D CAD models' volumes, total surface areas and moments of inertia, among others, enables the quick assessment of two models' geometric equivalency. Given its low computation cost and the availability of the compared metrics, such method

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has been used in CAD modeling management systems [26] and geometric validation mechanisms [8], [15].

Also called the “Cloud Of PointS” (COPS) mechanism [8], the point-to-part difference calculation method is based on the evaluation of the *Hausdorff metric* between the models’ surfaces. As pictured in Fig. 3(a), it measures the distance between two subsets of the 3D space, with one of the subsets being discretized into a point set. The location and evaluation of multiple local deviation maxima can be computed by dividing the models’ surfaces into smaller subdomains like faces (e.g. [13]) or local neighboring regions (e.g. [37]).

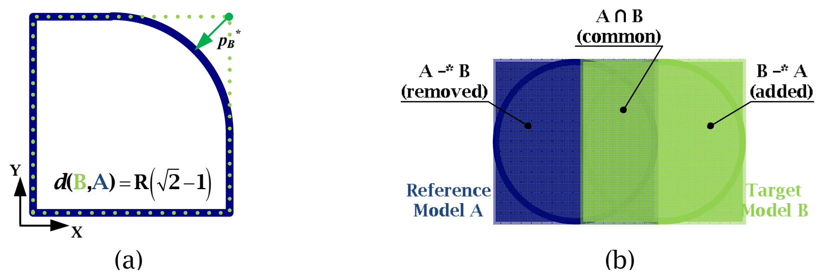

Fig. 3: Illustrating explicit geometric comparison methods: (a) Point-to-part deviation calculated between sampling points from part B and the boundary of part A, (b) Identifying regions of material removal and addition between parts in the spatial occupancy comparison method.

Figure 3(b) illustrates the basic principle on which relies the spatial occupancy comparison. Regions of material removal and material addition are distinguished from the common space occupied by both part models. The superposition of 3D shapes is the more straightforward way to compare spatial occupancy. Algorithms similar to those used to verify part mating, clearance and interference in DMU environments (e.g. [7]) are usually applied here. The calculation of the regularized Boolean operations from set theory between two solids can also be performed by a geometric modeling kernel (e.g. [31]). Likewise, the use of decomposition representations, such as voxels (e.g. [7]) and octree structures (e.g. [14]), to compare spatial occupancy can increase the method’s computational efficiency.

In the second approach for calculating model differences, i.e. comparing the models’ data structures, the most intricate part of the calculation task is the matching of equivalent model elements between data structures. Four (4) matching methods for model elements have been identified [22]:

- *Static identity-based matching* – matching elements via their persistent and unique identifier assigned upon creation and maintained through modification;
- *Signature-based matching* – using a specific subset of an element’s attributes or properties to find an equivalent counterpart;
- *Similarity-based matching*- associating model elements based on the measured similarity of their aggregated geometric and/or descriptive features;
- *Syntax-specific matching* – incorporating the semantics of the compared 3D CAD models’ data representation scheme in the matching of model elements; e.g. specific relationships between model elements.

Fundamentally, CAD shape data is either represented following the *procedural* or the *explicit* modeling approach. A procedural model is described in terms of the operation of a sequence of procedures (which may include the solution of constraint sets), as opposed to an explicit or evaluated model whose full details are immediately available without the need for any form of calculation [17].

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Procedural models may be evaluated in order to be compared to explicit models. The opposite is however unfeasible, as procedural models are not unique for a given explicit geometry. Common 3D CAD parametric feature–based modeling systems are known to produce hybrid models, as model histories or construction trees are procedural shape representations while 2D sketches used as input for modeling operations, among others, are explicit shape representations [21].

3 EVALUATION METHODOLOGY

This section presents an outline of the methodology used to perform the two series of evaluation trials on a set of existing 3D CAD model difference identification software tools. The details and results of each series are presented in the next two sections. In Section 4, the first series involves tools implementing the comparison of 3D CAD models by means of their respective procedural representations, i.e. via implicitly represented geometry. Then, the second series focuses on tools implementing the comparison of 3D CAD models via the explicit representations of the modeled shapes and is detailed in Section 5.

3.1 Engineering Change Management Scenario

Simulated 3D CAD model comparison scenarios are defined for each series of evaluation trials. As stated earlier, the objective of the evaluation trials is to assess if and how much existing MDI–capable software tools could efficiently contribute to the transposition of a shape change between two application–specific models. Consequently, both scenarios involve the elaborated description of a shape change distinguishing two successive versions of a mechanical part's 3D CAD model as it would occur, for example, during the impact analysis of an engineering change proposal.

The 3D CAD models' reference original versions were inspired from geometric model available in the *Engineering Shape Benchmark* [29]. Modified versions were then created according to a predetermined list of discrete modifications reproducing specific model difference calculation situations. How each tool processed these situations contributed to their evaluation. The lists and descriptions of the modifications are given for each series in the following sections. A repository of the models used for both series of evaluation trials is available online for download at Ref. [30].

3.2 Evaluated Comparison Tools

The selection of the 3D CAD model comparison software tools to be evaluated was based on the inventory and categorization of existing MDI–capable software tools presented in Ref. [5]. Tools were selected based on their availability, free of charge, for direct examination and manipulation, i.e. all tests were to be executed locally by the authors; not as part of demonstration sessions or executed by representatives from software editors. Accordingly, evaluated comparison tools were either fully licensed versions, or provisional trial license graciously supplied by software editors.

Selected tools were initially divided into four categories based on the software tools' primary function [5]:

- Three–dimensional (3D) CAD systems, enabling the creation, modification, analysis and optimization of 3D part and product models;
- Three–dimensional (3D) CAD visualization and collaboration tools, applied in the efficient viewing, manipulation, annotation and sharing of native or lightweight 3D CAD models;
- Three–dimensional (3D) CAD validation tools, originally designed to support the geometric validation of translated or remastered 3D CAD data; and
- Miscellaneous tools with some MDI capabilities.

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3.3 Preprocessing and Configurable Settings

When made available, support documentation for the evaluated comparison tools was examined to retrieve appropriate procedures to follow for the comparison of the 3D CAD models. The need for any preprocessing steps, such as pose registration, and the sets of configurable settings were also surveyed.

3.4 Evaluation Criteria and Rating Scale

Given the simulated shape change assessment scenarios, model differences identified between the 3D CAD models' versions need not only to be calculated, but also suitably represented and visualized. To that intent, inspired by shape–based retrieval literature [19], we defined five criteria on which to evaluate the results provided by the different MDI–capable software tools and their respective pair–wise comparison functions:

- EC#1. *calculation recall* – the ability of the difference calculation algorithm to locate all relevant differences without omissions (false negatives);
- EC#2. *calculation precision* – the quality of a difference calculation algorithm able to precisely locate relevant differences while avoiding false positives;
- EC#3. *representation range* – a quality that characterizes the level of detail and the amount of information provided in the description of the differences; and
- EC#4. *representation accuracy* – the quality of a function that accurately identifies and describes the nature of the located differences as per the corresponding representation range;
- EC#5. *visualization discernability* – the quality of a difference visualization mechanism that makes the identification and the perception of differences a relatively simple process.

Based on the compiled results and observations, software tools were rated according to the following 3–grade rating scale to specify to what extent each of them met the considered evaluation criteria:

- Good (ŏ ŏ ŏ), highlighting the tool's reliability with respect to the examined criterion in the identification and analysis of model differences;
- Fair (ŏ ŏ), indicating an acceptable performance level for the evaluated tool, despite some minor or generalized shortcomings/omissions; or
- Poor (ŏ), denoting the observation of major flaws or shortcomings, rendering the tools unfit for the assessment of engineering change.

4 COMPARING PROCEDURAL REPRESENTATIONS OF 3D CAD MODELS

Software tools providing MDI capabilities by means of procedural representation comparison were the subject of a first and distinct series of evaluation trials for two main reasons:

- The implemented difference calculation approach distinctively compares 3D CAD models represented implicitly via the tree–like structure of their geometric modeling operations instead of via explicit 3D geometry; and
- The applicability of this approach is strictly limited to MDI scenarios involving related 3D CAD models embodying versions of a given part.

4.1 Scenario

The shape change assessment scenario used as the setting for this first series involves two 3D CAD models embodying via procedural representation the successive versions of a mechanical part. Figure 4 presents the geometry of both the original and modified versions of the part. The original procedural model comprises 55 modeling operations, more than half of which are sketch–based

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extrusion features (35). Simple modeling operations, which also include holes, mirror patterns and datum planes, were used to build the models' modeling histories so that they could be easily retrieved and instantiated whatever the 3D CAD format the models were to be expressed in. The resulting explicit geometries purposely excluded complex geometric entities (e.g. NURBS curves and surface) to ensure the geometric reproducibility of the models when processed by different geometric modeling kernels.

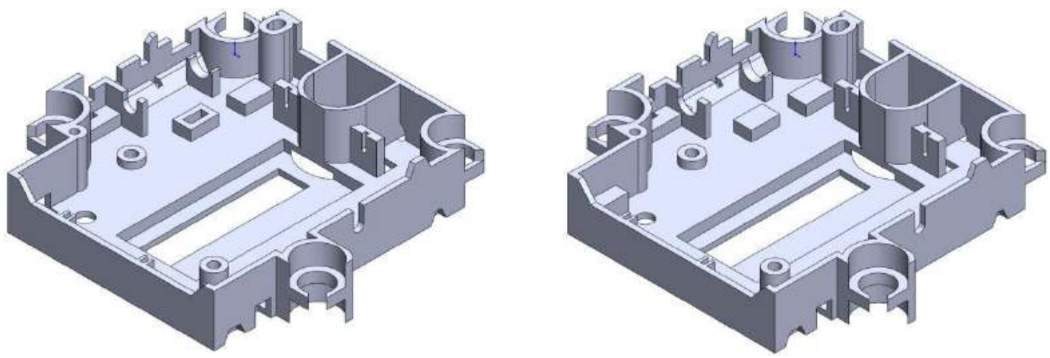

Fig. 4: Part geometry of the 3D CAD models used for the evaluation of tools implementing the comparison of procedural representations: (a) Original part (reference), (b) Modified part (target).

Since the comparison of procedural representations is only possible between homogeneously formatted models, each trial had to use a distinct pair of reference and target models. Target procedural models representing the part's modified geometry were generated by copying their respective reference models and by editing the copied models' modeling histories. The modifications differentiating the models to be compared are as follow:

- Thirteen (13) modeling operations were directly modified at the parametric level, i.e. one or more of their parameters had their value changed. One particular parametric change did not lead to any change in the resulting explicit geometry.
- Two (2) modeling operations were removed and two (2) modeling operations were added from the modeling sequence. Two of the removed/added operations had no geometric outcome. Also, two (2) modeling operations were reordered in the modeling sequence; only one led to a change in the target geometry.
- Two (2) modeling operations underwent metadata modifications, i.e. one had its identifying name modified, while the other had its related sketch's name modified.

In this first scenario, the outcome of the 3D CAD models' comparison was mainly to locate the differences and provide as much details as possible on their representation via modeling operations and related parameters. The comparison results were expected to enable an appropriate assessment of the engineering change represented by the two versions.

4.2 Evaluated Comparison Tools

Among all the inventoried software tools from Ref. [5], only three (3) implement the comparison of 3D CAD procedural representations. All three are 3D CAD systems and are listed in Table 1. For a systematic evaluation, a reference model and a target model were built with each 3D CAD system using the predetermined sequence of modeling operations. Minor differences between the reference

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models' modeling histories had to be tolerated due to the inherent heterogeneity of the modeling operations provided by the different 3D CAD systems.

Trial	*3D CAD system*	*Release*	*Ref.*
1	Dassault Systèmes SolidWorks®	2010 SP4.0	[31]
2	Siemens PLM NX®	7.0 MP1	[25]
3	Parametric Technology Corporation (PTC) Pro/ENGINEER®	Wildfire 5.0	[28]

Tab. 1: 3D CAD systems evaluated for their procedural model comparison capabilities.

4.3 Preprocessing and Configurable Settings

As observed in their respective support documentation, all three evaluated software tools account for the fact that the applicability of 3D CAD MDI via implicitly represented geometry is strictly limited to MDI scenarios involving related 3D CAD models embodying versions of a given part, i.e. models derived from one to another. Hence, the need for pose registration prior to the comparison was overlooked for these first trials since each pair of models was originally defined in the same coordinate system. Also, no configurable settings were to be adjusted prior to the comparison.

4.4 Results

Detailed results about the evaluation trials were compiled and are summarized in Table 2. Modeling operation counts for each of the six models' operation sequences took only first level parent operations into account, i.e. sketches or other child operations were not considered. In the cases where differences were specifically located in sketches or other child operations by the software tools, corresponding parent operations were implicitly considered as being different in the compiled results.

For all three systems, more modeling operations (22) were identified as being parametrically different than was originally intended in the scenario (13) – one of the systems locating nearly three times more modified modeling operations (36). This issue is mainly due to each system having its own set of rules regarding how to identify local parametric modifications and their ensuing impact on the overall target operation sequence and/or explicit geometry. For instance, in this particular scenario, later modeling operations impacted by modifications on preceding operations, such as mirror patterns referencing a modified seed operation, were unevenly identified as differences by the systems. The same behavior was observed for operations with sketches referencing modified explicit geometry. Thus, the counts for modified operations diverged, indicating variance in calculation precision (EC#2).

Removed/added modeling operations were all correctly located and accurately represented between the compared modeling histories. However, this was not the case for reordered operations and renamed objects. Only Pro/ENGINEER® explicitly identified two differences in the modeling sequences and two differences in the modeling trees' metadata. A major issue was also observed in trial #2 (NX®) regarding overall accuracy (EC#2 and EC#4), as some modeling operations were concurrently identified as both 'modified operations' and 'operations not compared'.

Except for reordered operations, modifications having no geometric outcome when applied to modeling histories were also generally detected as expected, denoting that the implemented difference calculation algorithms actually compares the 3D CAD models' modeling sequences and not their explicit geometric data. On the matter of representation accuracy (EC#4), results corresponding to parametric modifications not bearing a geometric outcome were inconclusive in trial #2 because no

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distinction could be made in the representation of the differences between those with a geometric outcome on the modeled part and those without.

As for the representation and visualization of comparison data, all three systems provided reporting functionalities to summarize and distribute the results. Interaction with both comparison and 3D geometric data was also possible in two out of three systems, enabling users to expand their analysis of the modified part. Nonetheless, 3D annotations locating the outcome of parametric modifications directly on the evaluated shapes would have improved discernability (EC#5). Relating to representation range (EC#3), the semantic value of 3D CAD procedural representations allows for detailed and significant comparison results as model differences were expressed in terms of, for example, an added blend radius, an increased wall thickness or displaced holes with respect to local references, etc. However, changed values for modeling operation parameters were not systematically specified as part of the comparison results. While Pro/ENGINEER® provided original and modified values for parameters from both modeling operations and sketches (e.g. dimensions), SolidWorks® provided similar data for only first-level modified modeling operations, excluding sketches.

	Scenario	*Trial #1*	*Trial #2*	*Trial #3*
Software tool	--	SolidWorks®	NX®	Pro/ENGINEER®
*Modeling operation counts**				
– Reference model	55	55	55	56
– Target model	55	55	55	56
Differences between histories				
– Modified operations	13 (24%)	22 (40%)	36 (65%)	22 (39%)
– Removed operations	2 (4%)	4 (7%)	2 (4%)	2 (4%)
– Added operations	2 (4%)	4 (7%)	2 (4%)	2 (4%)
– Reordered operations	2 (4%)	--	--	2 (4%)
– Renamed objects	2 (4%)	--	--	2 (4%)
– Operations not compared	--	--	10 (18%)**	--
Changes w/o geometric outcome				
– Parametric modification	--	Located	Inconclusive	Located
– Removed/added operations	--	Located	Located	Located
– Reordered operation	--	Not located	Not located	Located
Representation & visualization				
– Changed parameter values	--	Partial	No	Yes
– Reporting	--	Yes	Yes	Yes
– 3D interaction	--	Yes	No	Yes
Evaluation criteria				
#1. Calculation recall	--	ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ
#2. Calculation precision	--	ǒ ǒ	ǒ	ǒ ǒ
#3. Representation range	--	ǒ ǒ	ǒ	ǒ ǒ ǒ
#4. Representation accuracy	--	ǒ ǒ	ǒ	ǒ ǒ ǒ
#5. Visualization discernability	--	ǒ ǒ	ǒ	ǒ ǒ

* Subordinate operations such as sketches or patterned features are omitted.
** Three (3) hole operations were simultaneously identified has “changed” and “not compared”.

Tab. 2: Results from evaluation trials of history-based model comparison software tools.

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5 COMPARING EXPLICIT GEOMETRY

Explicit geometry comparison algorithms, whether they compare geometric data structures such as B–Rep data structures or other explicit geometric representations, are the type most widely implemented by 3D CAD MDI–capable software tools. As opposed to procedural representation comparison, corresponding difference calculation methods are various, having a direct influence on the representation and visualization of comparison results. Hence, the second series of evaluation trials focused primarily on the quality of the different comparison functions implemented by the inventoried software tools to locate and elaborate on basic geometrical and topological differences between two 3D CAD models.

5.1 Scenario

This second shape change assessment scenario involved the comparison of the original and modified versions of a mechanical part embodied by a reference and a target ISO STEP [18] file, respectively. All trials were to be performed using a single pair of STEP files comprising only explicit geometric data (B–Rep). No procedural representations were available for comparison.

Surface types now included planar, cylindrical, conic and B–spline surfaces. Figure 5 shows the geometry of both the original and the modified modeled parts, the latter appended with labels identifying the modified regions. Table 3 gives an outline of the thirteen (13) modifications applied to these specific regions, specifying if changes were to be expected in either the target model's topology, geometry or both, and providing the resulting maximum deviation for each geometric difference.

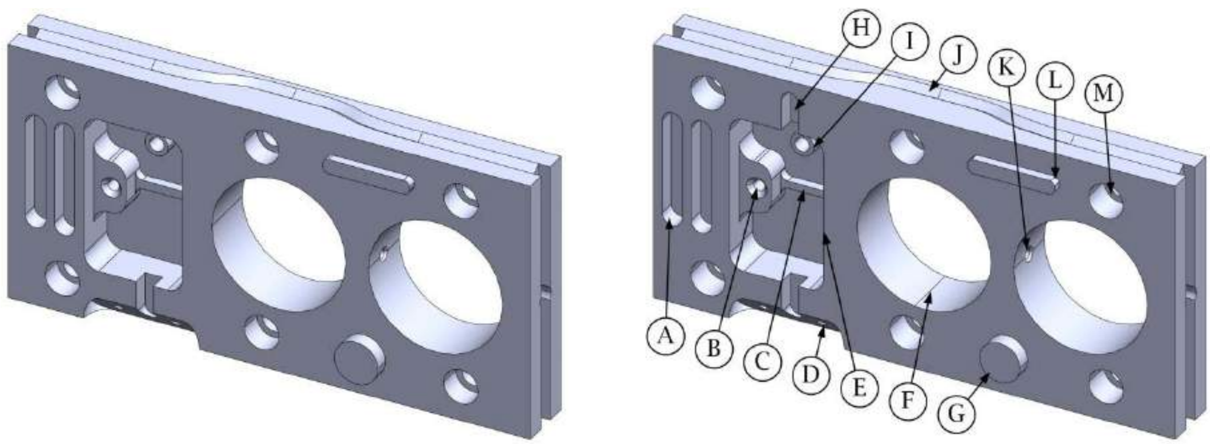

Fig. 5: Geometry of the modeled parts used for the evaluation of software tools implementing an explicit geometry comparison for MDI purposes: (a) Original part (reference), (b) Modified part (target) with the modified regions indicated.

The purpose of this second shape change assessment scenario was primarily to locate the geometric differences between the two modeled shapes. The location of simple topological differences was also evaluated, as the topological equivalency of 3D CAD models' boundary representations may become critical in some given cases (e.g. NC tool paths calculation). A tolerance value of 0.05 mm was to be set for all trials to filter infinitesimal and/or irrelevant geometric deviations from the calculated results. Additional information on the located differences, such as counts, difference regions and deviation measurements, among others, was also to be investigated as such elaboration furthers the assessment of the engineering change between the two versions.

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Label	Modification	Type(s) of model change: Size	Location	Geometric	Topological	Estimated maximum deviation
A	Two-slot pattern, moved laterally		X			3.8 mm
B	Countersunk hole, diameter reduced	X				0.07 mm
C	Rib, width reduced	X			X	0.3 mm
D	Blind holes' bottoms, changed from conic to flat			X	X	0.8 mm
E	Pocket, width reduced (from labeled side)	X				1.6 mm
F	Through hole, inner faces split				X	--
G	Circular boss, moved and diameter reduced	X	X			1.3 mm
H	Blind slot, added			X	X	7.6 mm
I	Circular boss, tapered side			X		0.2 mm
J	Swept cut, modified trajectory			X		0.6 mm
K	Chamfer, surface equation changed			X	X	0.08 mm
L	Rectangular boss, rounds replaced by chamfers			X		0.2 mm
M	Six-hole pattern, counterbore's depth increased	X				2.5 mm

Tab. 3: Outline of the modifications differentiating the reference and target 3D CAD models.

5.2 Evaluated Software Tools

The list of software tools that were evaluated within the second series of trials is presented in Table 4 and organized according to the different categories of 3D CAD model comparison tools proposed in Ref. [5]. In some cases, more than one comparison function was available for trial; the names of these functions are also listed, making up for a total of twenty (20) trials.

Very few to no details were available to investigate the exact nature of each difference calculation approach employed, which is understandable in a commercial context. Since only deductions could be made from the representation and visualization of the comparison results for most of the evaluated tools, it was considered better not to identify the difference calculation methods systematically. As a substitute, brief descriptions of the graphical presentation of the comparison results are provided for each trial.

Trial #19 exceptionally involved a 3D CAD model comparison tool, CapVidia CompareVidia [13], primarily designed for CAD data translation validation. Though it does not naturally belong to the MDI solution domain, the focus of the evaluation trials, this particular software tool was still included in the trials as it does implement MDI capabilities to warrant validation results.
Also, trial #20 involved PolyWorks® from InnovMetric Software [27], a computer-assisted inspection software capable of comparing sets of points representing actual measured parts to reference 3D CAD models. To exploit the software's comparison capabilities for MDI purposes, the target STEP model

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was first converted into a point cloud using the CATIA® V5 [7] *STL Rapid Prototyping* workbench and, then, compared to the reference STEP model.

Software tool	*Release*	*Evaluation license*	*Ref.*	*Trial*	*Evaluated functions*
3D CAD systems					
Autodesk® Inventor® Fusion	0.3		[3]	1–	Change Manager
Dassault Systèmes CATIA® V5	R18 SP8		[7]	2– 3–	Graphical comparison Geometric comparison
Dassault Systèmes SolidWorks®	2010 SP4.0		[31]	4– 5–	Compare volumes Compare faces
Missler Software TopSolid®	2008		[36]	6–	Shape compare
PTC CoCreate® Modeling PE	2.0		[11]	7–	Compare parts
PTC Pro/ENGINEER®	Wildfire 5.0		[28]	8–	Compare by geometry
Siemens PLM NX®	7.0 MP1		[25]	9– 10–	Model comparison Geometric comparison
SpaceClaim® Engineer	2011.1 SP1	X	[33]	11–	Color modified faces
3D CAD visualization and collaboration tools					
Actify SpinFire™	9.0	X	[34]	12–	Model Compare
Adobe Systems Acrobat® Pro 3D Reviewer®	9.4 SP4		[2]	13–	Compare
C4W 3D Shop ModelScan	2.8.4	X	[1]	14–	Compare
Lattice Technology XVL Studio© Professional	9.1a	X	[37]	15– 16– 17–	Simple shape compare View shape compare Difference detection
Oracle AutoVue® Electro–Mechanical Professional	20.0	X	[4]	18–	Compare
3D CAD validation tools					
CapVidia CompareVidia	1.0	X	[13]	19–	Compare
Other 3D software tools					
InnovMetric Software PolyWorks®	11.0		[27]	20–	Inspect

Tab. 4: Software tools and functions evaluated for their explicit geometry comparison capabilities.

5.3 Preprocessing and Configurable Settings

Some variance was observed among the evaluated software tools regarding the availability and/or the condition of the user–adjustable settings regulating difference calculation. For example, four (4) functions did not allow a tolerance value to be set by the user prior to being executed. Neither the software tools' user interfaces nor their respective help documentation provided evidence of the

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existence of such a parameter or of other parameters that could serve the same purpose. For the evaluation trials where no tolerance settings were available, it was therefore predicted that geometric deviations less than 0.05 mm, as per specified in other trials, could possibly be detected.

The computing accuracies of the various comparison functions were also regulated differently. Six (6) of the experimented functions provide parameters to regulate shape approximation or surface point sampling specifically for comparison. Eight (8) other functions relied indirectly on either their respective tools' display accuracy setting or on some previously–specified data importation settings. As for the six (6) remaining functions, the computing accuracy was not user–adjustable. Nonetheless, trials were conducted with computing accuracies set at their respective default setting. In the event of trials exhibiting issues regarding difference calculation recall (EC#1) for the given modifications, arbitrary computing accuracies would have been identified as a possible cause.

As a preliminary operation for the comparison process, all the tested functions required that the compared shapes undergo pose registration. However, this preprocessing was determined to be unnecessary since the reference and target models embodied versions of the same part and, therefore, were defined beforehand in the same coordinate system. Still, if pose registration had to be performed, fourteen (14) of the evaluated functions provided means to register the poses of the models prior to the comparison. Nine (9) functions provided means to align geometries according to either pre–defined (4) or transient custom–defined (5) coordinate systems, while five (5) functions allowed manual pose registration via external DMU editing operations.

5.4 Results

To begin with, two (2) of the model comparison tools listed in Table 4, along with their corresponding trials, presented critical issues related to their application in the simulated shape change assessment scenario. Essentially, both could not compare STEP files exclusively, as detailed here:

- Trial #1 on the Autodesk® Inventor® Fusion [3] software could not be performed using the original pair of reference and target STEP files. The software's *Change Manager* module is designed to identify and convert explicit modifications applied to an evaluated (explicit) model back to a reference procedural representation, which cannot be provided via a STEP file.
- Trial #11 could not be performed on SpaceClaim® Engineer [33] either, because the tool's comparison functionalities can only be used on related versions of the same native–formatted 3D CAD model. Such particularity is typical of a static identity–based matching algorithm used for calculating shape differences. In the simulated scenario, the persistent identifiers exploited by this type of algorithm were inherently inexistent in the outsourced STEP files.

Table 5 presents a summary of the evaluation results for the twenty (20) trials, including trials #1 and #11 for which supplemental tests were performed and are discusses in Section 5.5. Besides each trial's evaluation regarding the five (5) evaluation criteria, the table includes brief descriptions of the graphical output for each comparison functions, identifies corresponding types of utility functions performing pose registration and, in specific cases, highlights which difference metric is provided.

One particular function failed to execute properly and, thus, no result are available for the corresponding trial (#4). It was observed that the regularized Boolean operations performed on the compared solids resulted in new solids with infinitesimal boundary entities that the processing geometric modeling kernel ultimately could not handle. Further investigation identified blended/rounded regions as one of the causes of the failure.

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5.4.1 Calculation Recall and Precision (EC#1 & EC#2)

The aspect of difference calculation refers to the capacity of the software tools and their respective comparison functions to locate all (EC#1) and only (EC#2) relevant shape differences between the compared STEP files. Accordingly, seven (7) trials were rated with good calculation recall (EC#1) and ten (10) trials were rated with good calculation precision (EC#2).

Minor issues relating to calculation recall (EC#1) mostly concerned the location of modification 'A' and 'F'. Modification 'A' involved the leftward translation of the two–slot pattern by a distance equal to the width of the resulting rib between the slots. As pictured in Fig. 6, this ultimately led to two interior planar faces from the slot features, one from the reference model and one from the target model, to possess equivalent boundary edges and equivalent surface geometric definition, except solely for their respective normal vectors, which were opposed.

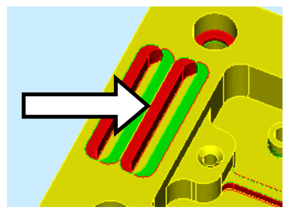

Fig. 6: Coincident planar faces with opposed normal vectors from the two–slot patterns.

This particular geometric singularity affected seven (7) trials in which the comparison functions inaccurately matched the two coincident yet unrelated planar faces and, thus, did not completely locate the difference. These particular functions calculate differences via the B–Rep entities of the compared models. Modification 'F', which involved only a topological difference in the subdivision of a cylindrical face, was simply not located in eight (8) trials. For some of those trials, it was observed that the software tools altered the models' topology prior to comparison. As a result of their respective STEP file importation processes, modification 'F' was systematically removed, cancelling beforehand the topological difference that could then not be located. This issue could be resolved by appropriately configuring, when possible, the tools' STEP file importation modules in order to preserve the STEP models' topology during the importation process. Still, the observed behavior highlights the possible loss and/or degradation of original 3D CAD data when submitted to a translation process. When comparing 3D CAD models, such data degradation originating from the model comparison tool's processing of the CAD data would logically overthrow the process that it is precisely designed to perform.

Poor calculation recall was attributed in four (4) trials as the corresponding functions overlooked differences bearing small deviations (e.g. modifications 'B', 'I', 'K' and 'L'). No tolerance value could be set prior to comparison for these specific functions, which led to conclude that the default settings were greater than the preset 0.05 mm for all other trials.

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Software tool	*Trial*	*Graphical output*	*Pose registration*	*Metric*	*EC#1*	*EC#2*	*EC#3*	*EC#4*	*EC#5*
3D CAD Systems									
Autodesk® Inventor® Fusion	1–	Procedural changes*	--	Parameters	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ	ǒ ǒ
Dassault Systèmes	2–	Superposed shapes	CSYS align	--	ǒ	ǒ	ǒ	ǒ ǒ	ǒ
CATIA® V5	3–	Colored outlying voxels	CSYS align	--	ǒ ǒ ǒ	ǒ	ǒ	ǒ ǒ	ǒ ǒ
Dassault Systèmes	4–	Solids models	CSYS align	--	--	--	--	--	--
SolidWorks®	5–	Classified faces	CSYS align	--	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ
Missler Software TopSolid®	6–	New faces	Custom align	--	ǒ ǒ	ǒ ǒ ǒ	ǒ	ǒ ǒ ǒ	ǒ ǒ
PTC CoCreate® Modeling PE	7–	Classified faces	Custom align	Deviations	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ
PTC Pro/ENGINEER®	8–	Out-of-tol. facets	--	--	ǒ ǒ	ǒ ǒ ǒ	ǒ	ǒ ǒ ǒ	ǒ
Siemens PLM NX®	9–	Classified faces	Custom align	--	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ
	10–	Classified faces	Custom align	--	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ
SpaceClaim® Engineer	11–	Classified faces*	--	Dimensions	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ
3D CAD visualization and collaboration tools									
Actify SpinFire™	12–	Superposed shapes	Manual	--	ǒ	ǒ	ǒ	ǒ ǒ	ǒ
Adobe Acrobat® Pro 3D Reviewer	13–	Out-of-tol. facets	Manual	--	ǒ ǒ	ǒ ǒ ǒ	ǒ	ǒ ǒ ǒ	ǒ
C4W 3D Shop ModelScan	14–	Unique faces	--	--	ǒ ǒ ǒ	ǒ ǒ	ǒ	ǒ ǒ ǒ	ǒ
Lattice Technology	15–	Unique faces	Manual	--	ǒ ǒ ǒ	ǒ ǒ	ǒ	ǒ	ǒ
XVL Studio® Professional	16–	Superposed shapes	Manual	--	ǒ	ǒ	ǒ	ǒ ǒ	ǒ
	17–	Facets w/ color scale	Manual	Deviations	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ
Oracle AutoVue® Electro-Mechanical Professional	18–	Superposed shapes	--	--	ǒ	ǒ	ǒ	ǒ ǒ	ǒ
3D CAD validation tools									
CapVidia CompareVidia	19–	Facets w/ color scale	--	Deviations	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ	ǒ	ǒ ǒ ǒ
Other 3D software tools									
InnovMetric Software PolyWorks®	20–	Out-of-tol. points	Custom align	Deviations	ǒ ǒ	ǒ ǒ ǒ	ǒ ǒ	ǒ ǒ ǒ	ǒ

* Results from additional evaluation trials require to overcome incapability to compare STEP fil es (see Section 5.5).

Tab. 5: Results from evaluation trials of explicit geometric model comparison software tools.

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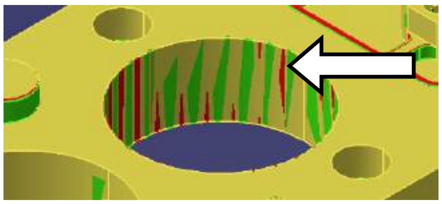
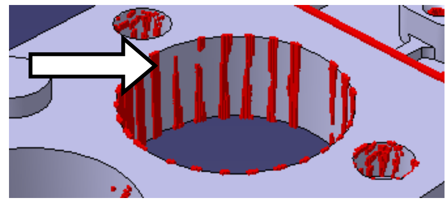
Concerning calculation precision (EC#2), no clear distinction could be made in some trials between the geometric differences due to the explicit modifications described in Table 3 and those resulting indirectly from parent or neighboring modified features. In a scenario involving the detailed assessment of engineering change, such a distinction is key. However, the most significant case of poor calculation precision (EC#2) involved modification 'F' and five (5) comparison functions relying on approximated shape (via tessellations or voxels) to calculate differences. As pictured in Fig. 7, the comparison of two locally equivalent geometries, which were approximated differently due to the inherent topological difference, notably led to the visual location of false geometric deviations within the central large opening of the target model. In a few trials, differences were also located on some other cylindrical faces that did not present any topological differences.



(a)



(b)

Fig. 7: Representations of erroneous geometric deviations due to shape approximation: (a) Superposed 3D tessellated shapes, (b) Voxel approximation.

Additional trials focused on these specific functions showed that this problematic behavior could be avoided by increasing or "loosening" the difference tolerance value. However, the downside of such a work-around is that other small yet critical differences will be wrongfully filtered out and thus overlooked. Increasing the computing accuracies of these functions prior to comparison, when possible, reduced the number of false geometric deviations, but also increased computing time, especially in the case of voxel approximation.

5.4.2 Representation Range and Accuracy (EC#3 & EC#4)

The range of difference representation (EC#3) relates to the amount and quality of information provided by a comparison function in the description of the located differences, while the accuracy (EC#4) characterizes its capability to rightly describe such differences. Generally, it was observed that simple, but poor representation ranges, e.g., unchanged/changed or added/removed classifications, were mostly associated with accurate representation capabilities. Conversely, comparison functions providing more elaborated differences classifications and descriptions were found less accurate in identifying the correct description of the differences.

Good representation range was notably attributed to comparison functions promptly providing metrics in the form of parametric or dimensional differences, or in the form of local geometric deviations. In many cases, such measures could be obtained using external measuring utility functions, but there were not taken into account in this particular evaluation due to the fact that they were not part of the actual comparison functions.

Minor issues leading to some trials' fair representation accuracy (EC#3) ratings include side effects of poor calculation precision, i.e., the description of false differences, and inaccuracies in faces classifications. For example, large geometric deviations between corresponding faces from reference and target models (e.g., modifications 'A' and 'M') seldom prevented them to be matched and

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accurately described as modified. Poor representation accuracy (EC#3) involved more significant disorganization in face mapping and classification.

The representation range and accuracy greatly affect the application of a giving function in a shape change assessment scenario. For example, modifications 'C' and 'E' involved the perpendicular translation of planar faces in the large pocket area. As a result, the blended faces from related round features were also identified as being geometrically different, in some cases even topologically, even though no modifications were applied directly to the round features. Since not enough additional information is provided, it is impossible to identify key details such as whether the radii of the round features were actually modified or if they were simply moved along with a tangent face.

5.4.3 Visualization Discernability (EC#5)

Good visualization discernability was attributed to trials in which the graphical output of the comparison could be easily explored and inspected by means of selectable difference lists, elaborated viewing filters or even cross–sections. Those at least providing separate synchronized views of the reference and target models were given a 'fair' rating.

The nine (9) remaining trials presented the comparison results via the visualization of superposed 3D shapes, which notably rendered the visual examination of modification 'A' impossible, as shown in Fig. 6. Accordingly, comparison functions relying solely on 3D shape superposition presented visualization discernability (EC#5) issues when it came to locating small yet pertinent geometric differences. In the specific cases of modifications 'B' and 'L', differences were actually correctly located. However, since the comparison results were exclusively visual, the superposed models' views had to be zoomed in considerably to be observable. This is obviously impractical, because the exact location of the differences cannot be known beforehand. The risk of potentially overlooking relevant differences in cases where the comparison takes place between larger and more complex 3D shapes is therefore significant.

5.5 Additional Evaluation Trials

Additional trials were performed on both Autodesk® Inventor® Fusion's Change Manager [3] and SpaceClaim® Engineer [33] to round out the second series of evaluation trials. The goal was again to evaluate the tools' MDI–capabilities, but without regard to their inability to compare two outsourced models. In both trials, the shape change assessment scenario was altered to involve the same two versions of the part, but in native formats instead.

On aspects such as calculation recall (EC#1) and precision (EC#2), the additional trials lead to satisfying results, with at least all twelve (12) modifications bearing a geometric outcome on the modeled shape being exclusively and accurately located. Also, good results were generally observed relating to representation range (EC#3) and accuracy (EC#4), as compared to the results of the eighteen previous trials. For example, SpaceClaim® Engineer provides a useful dimensioning function to measure user–defined part dimensions simultaneously on both the reference and target shapes, helping users to further elaborate on the description of a shape change.

By relating explicit geometric differences back to a reference procedural representation of the model, Autodesk® Inventor® Fusion's Change Manager enables some shape differences to be elaborated in terms of revised modeling operations and corresponding parametric modifications. A distinction between source and impacted geometric differences, such as in the cases of the translated blended faces induced by modifications 'C' and 'E', is thus possible. However, the description of differences according to this elaborated representation range is far from accurate. Since converting explicitly represented modifications into procedural form is not a simple task, only simple isolated

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modifications are accurately represented, the remaining being insufficiently converted into low–level boundary edits.

6 CONCLUSION

Any decision regarding the selection of the proper model comparison tool must be influenced primarily by the problem at hand and the product lifecycle process to provide for. The results presented in this paper from the two series of evaluation trials performed on commercially available 3D CAD model comparison tools confirm such assertion. As it was intended to assess how these software tools could efficiently contribute to the shape change transposition problem, the significant variance observed in the model difference calculation algorithms implemented and, consequently, in the comparison results presented, leads us to discern that no MDI technology can be applied conveniently whatever the model comparison scenario.

Five evaluation criteria were defined to symbolize the basic requirements of two simulated shape change assessment scenarios, emphasizing on the need for detailed and significant comparison results in the engineering change management application domain. As far as geometric differences could acceptably be located (EC#1) between versions of either procedural or explicit 3D CAD models, major concerns arisen relating to other criteria:

- Comparing procedural models will provide more insight on the rationale for a shape change as model differences are located and measured in terms of semantically valued modeling operations, upholding the representation range criterion (EC#3). Yet, the first series of evaluation trials revealed concerns for both difference calculation precision (EC#2) and representation accuracy (EC#4) for the evaluated comparison tools, as no clear distinction could be made between modified operations and those geometrically or chronologically impacted by the modifications.
- The use of shape approximations to calculate model differences between explicit 3D CAD models must be avoided in shape change assessment scenarios. On top of providing approximate measures of the located differences (EC#4), it generated geometric "noise" that could not be distinguished from small yet possibly significant geometric deviations given the context (EC#2). The use of exact shape representations, such as B–Rep, must therefore be preferred.
- MDI tools relying exclusively on the graphical representation and visualization of model differences are exposed to critical discernability issues (EC#5). The absence of simple reporting functions in some comparison tools, usually provided to support the graphical visualization of differences, renders some accurately located shape differences unnoticeable by the common user, unless he knows beforehand where to look, which is impractical in a shape change assessment scenario.

Shape change transposition – i.e., enabling rapid and reliable decision making in a prescribed use context via the adequate representation of 3D CAD model differences – ultimately calls for precise difference calculation and elaborated difference representation. In the light of the observations stemming from the two series of evaluation trials and the conclusions drawn from our previous review [5], the next generation of MDI solutions capable of supporting shape change transposition ought to integrate the precision and flexibility of existing explicit B–Rep–based calculation methods with a representation range comparable to the one of procedural CAD model comparison. Notably, description of model differences at the level of actual engineering semantics must be made possible for the comparison of application–specific, thus heterogeneously formatted, 3D CAD models.

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Furthermore, difference representation and visualization constitute two parts of the MDI problem which must be addressed separately as much as possible, as it was observed that the joint graphical approach leads to precision and discernability issues. Representation of 3D CAD model differences should not be considered as a transient stage between the calculation and the visualization of comparison results, but as the keystone of efficient difference analysis and subsequent manipulation. It is the authors' opinion that a proper representation of calculated model differences is at the basis of any good visualization scheme, whatever the application for 3D CAD model comparison.

REFERENCES

[1] 3D Shop ModelScan, www.c4wviewer.com/accueil-en.html, C4W.

[2] Acrobat 9.0 Pro Extended: 3D Reviewer, www.adobe.com/products/acrobat.html, Adobe Systems inc.

[3] Autodesk Inventor Fusion Technology Preview, labs.autodesk.com/technologies/fusion/, Autodesk inc.

[4] AutoVue Electro-Mechanical Professional, www.oracle.com/us/products/applications/autoVue/autovue-electro-mechanical-professional/index.html, Oracle Corporation.

[5] Brière-Côté, A.; Rivest, L.; Maranzana, R.: Comparing 3D CAD models: Uses, Methods, Tools and Perspectives, Computer-Aided Design and Applications, 9(6), 2012, 771-794. http://www.cadanda.com/TOCV9No6.html.

[6] Cardone, A.; Gupta, S.K.; Karnik, M.: A survey of shape similarity assessment algorithms for product design and manufacturing applications, Journal of Computing and Information Science in Engineering, 3(2), 2003, 109-118. http://dx.doi.org/10.1115/1.1577356.

[7] CATIA V5, www.3ds.com/products/catia/, Dassault Systèmes inc.

[8] CAx Implementor Forum: Recommended Practices for Geometric Validation Properties, 2008, 85 pp. Available: http://www.cax-if.de/documents/caxif_gvp_recprac.pdf (Accessed September 2012).

[9] Cessna Aircraft Company: Cessna Supplier Guidelines and Requirements for Engineering Certification Projects, 2010, 27 pp. Available: https://www.supplier.cessna.com/quality/requirements_for_engineering_projects.pdf (Accessed September 2012).

[10] Chowdhury, S.; Siddique, Z.: Development and implementation of shape comparison of 3D CAD models, 2009 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2009, August 30, 2009 - September 2, 2009, vol. 2, PART B ed, American Society of Mechanical Engineers, San Diego, CA, United states, 2009, 1085-1094. http://dx.doi.org/10.1115/DETC2009-87291.

[11] CoCreate Modeling Personal Edition 2.0, www.cocreate.com/products/PE2/ModelingPE2.aspx, Parametric Technology GmbH.

[12] CoCreate Software GmbH; Gutierrez, S.: Method for comparing a first computer-aided 3D model with a second computer-aided 3D model, U.S. Patent Application 2010/0135535, June 3, 2010.

[13] CompareVidia, www.capvidia.com/products/comparevidia, CapVidia NV.

[14] François, V.; Cuillière, J.C.: 3D automatic remeshing applied to model modification, CAD Computer Aided Design, 32(7), 2000, 433-444. http://dx.doi.org/10.1016/S0010-4485(00)00028-2.

[15] Frechette, S.P.: Interoperability Requirements for CAD Data Transfer in the AutoSTEP Project, U.S. Departement of Commerce, Technology Administration, 1996, 28 pp. Available: http://www.mel.nist.gov/msidlibrary/doc/ReqCadProj96.pdf (Accessed September 2012).

© 2013 CAD Solutions, LLC, http://www.cadanda.com

[16] Huang, Z.; Tian, S.; Zhou, J.: Solving CSG equations for checking equivalency between two different geometric models, Computer Aided Design, 36(10), 2004, 975–992. http://dx.doi.org/10.1016/j.cad.2003.10.002.

[17] International Organisation for Standardization: Industrial automation systems and integration -- Product data representation and exchange -- Part 108: Integrated application resource: Parameterization and constraints for explicit geometric product models, International standard ISO 10303-108:2005, International Organisation for Standardization, Geneva, 2005.

[18] International Organisation for Standardization: Industrial automation systems and integration -- Product data representation and exchange -- Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies (modular version), International standard ISO/DIS 10303-203:2010, International Organization for Standardization (ISO), Geneva, Switzerland, 2010.

[19] Iyer, N.; Jayanti, S.; Kuiyang, L.; Kalyanaraman, Y.; Ramani, K.: Three-dimensional shape searching: state-of-the-art review and future trends, Computer Aided Design, 37(5), 2005, 509-530. http://dx.doi.org/10.1016/j.cad.2004.07.002.

[20] Jackson, C.; Buxton, M.: The Design Reuse Benchmark Report: Seizing the Opportunity to Shorten Product Development, Aberdeen Group, Inc., Boston, MA, 2007. Available: http://www.aberdeen.com/aberdeen-library/3908/DesRes_Out_3908.aspx (Accessed September 2012).

[21] Kim, J.; Pratt, M.J.; Iyer, R.G.; Sriram, R.D.: Standardized data exchange of CAD models with design intent, Computer-Aided Design, 40(7), 2008, 760-777. http://dx.doi.org/10.1016/j.cad.2007.06.014.

[22] Kolovos, D.S.; Di Ruscio, D.; Pierantonio, A.; Paige, R.F.: Different models for model matching: an analysis of approaches to support model differencing, Proceedings of 2009 ICSE Workshop on Comparison and Versioning of Software Models (CVSM 2009), 17 May 2009, Vancouver, Canada, IEEE, Piscataway, NJ, USA, 2009, 1-6. http://dx.doi.org/10.1109/CVSM.2009.5071714

[23] Lockett, H.; Guenov, M.: Similarity measures for mid-surface quality evaluation, CAD Computer Aided Design, 40(3), 2008, 368-380. http://dx.doi.org/10.1016/j.cad.2007.11.008.

[24] Msaaf, O.; Maranzana, R.; Rivest, L.: Part data mining for information re-use in a PLM context, Proceedings of GT2007, May 14-17, Montreal, Canada, ASME Paper: GT2007-27966, American Society of Mechanical Engineers, New York, NY, 2007. http://dx.doi.org/10.1115/GT2007-27966.

[25] NX 7.0, www.plm.automation.siemens.com/fr_fr/products/nx/index.shtml, Siemens PLM Software inc.

[26] Parametric Technology Corporation; Gear, P.J.; Visser, B.J.: Method of comparing parts, U.S. Patent 6,625,607, September 23, 2003.

[27] PolyWorks V11, www.innovmetric.com/polyworks/3D-scanners/home.aspx?lang=en, InnovMetric Softwares Inc.

[28] PRO/Engineer Wildfire 5.0, www.ptc.com, Parametric Technology Corporation.

[29] Purdue Center for Information Systems in Engineering: Engineering Shape Benchmark, http://shapelab.ecn.purdue.edu/Benchmark.aspx. (Accessed August 2010).

[30] Rivest, L.: Professeur Louis Rivest - Research Webpage: CAD Model Comparison, http://profs.etsmtl.ca/lrivest/Recherche/index.html. (Accessed September 2012).

[31] SolidWorks 2010, www.solidworks.com, Dassault Systèmes.

[32] Souaissa, K.; Cuillière, J.-C.; François, V.; Benamara, A.; BelHadjSalah, H.: Automatic modification retrieval between CAD parts, Mécanique & Industries, 11(2), 2010, 85-92. http://dx.doi.org/10.1051/meca/2010020

[33] SpaceClaim Engineer 2011+, www.spaceclaim.com, SpaceClaim Corporation.

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[34] Spinfire 9.0, http://www.actify.com/products/spinfire-product-suite-cad-solution-system, Actify, Inc.

[35] Sypkens Smit, M.; Bronsvoort, W.F.: The difference between two feature models, Computer-Aided Design and Applications, 4(6), 2007, 843-851. http://www.cadanda.com/cad_4_6__11.pdf.

[36] TopSolid 2008, www.topsolid.fr/, Missler Software.

[37] XVL Studio Professional, www.lattice3d.com/products/products_studio_3d_software.html, Lattice Technology inc.

[38] Yang, Y.; Lin, H.; Zhang, Y.: Content-based 3-D model retrieval: A survey, IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews, 37(6), 2007, 1081-1098. http://dx.doi.org/10.1109/TSMCC.2007.905756.

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