Feature-Based Model Difference Identification for Aerospace Sheet Metal Parts

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Abstract. A semantic model difference identification (MDI) solution can be defined as an MDI solution that identifies and represents the differences between two compared models in terms of meaningful engineering information. Semantic representation of the differences between 3D CAD models is especially challenging due to the variety of modeling solutions used across industries, the non-uniqueness of modeling sequences and the use of low-level information, e.g. B-rep STEP files, in engineering communications. This work proposes an MDI method that represents the differences between 3D CAD models based on engineering semantics through features. Brake- and hydro-formed aerospace sheet metal parts are used as the application domain in which to propose and illustrate the proposed method. This method consists mainly of a pose registration stage and a difference identification stage. The pose registration method considers that all the features of a part serve specific functions, some of which are fundamental to the part's essential functionality, and that they are intertwined with the design intent of the part, which is particularly true for aerospace sheet metal parts. This provides the opportunity to semantically register feature-based 3D CAD models according to the unique purpose of the features in this specific domain of application. Difference identification is approached by primarily identifying and segregating the commonality between the compared 3D CAD models and then identifying the differences. The differences between 3D CAD models are classified as added, removed or differed features. Differed features are those features that are of the same type, but whose definition varies. As an outcome, the proposed method describes a way to fully pose-register 3D CAD models and identify their differences semantically based solely on their features, and, by extension, their design intent.

Keywords: CAD model difference identification (MDI), Aerospace sheet metal, Semantic, Feature-based registration, Feature-based comparison.
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1   INTRODUCTION

Information reuse is one of the most prominent strategies to improve efficiency throughout a product's life cycle, and it is applicable to all activities related to product development [1]. Information reuse can basically be divided into retrieving useful information and identifying the useful part of retrieved information[2].

In a scenario in which a process planer benefits from reusing the process plans of parts similar to the current project's part, a 3D shape search solution enables finding the similar models. In addition, a Model Difference Identification (MDI) solution would identify and measure the differences between the models to facilitate reuse of their process plans according to their differences. In another case scenario, a model of a part is distributed, for example between design partners, and modified unilaterally. The MDI solution would identify and measure the difference between the versions of the model and help evaluate and approve the modifications. In these scenarios, it is important that the differences are identified and represented at an appropriate semantic level to support rationalizing their impact on their related downstream engineering tasks and to facilitate user interactions.

The above-mentioned scenarios reveal the importance of MDI in effective information reuse and engineering work. The ability of an MDI method to represent the differences in an engineering-wise informative way is key to facilitate information reuse. Although MDI solutions and methods exist, representing the differences in a semantic way has not been addressed. For example, where the difference between two models is the displacement of a hole, available solutions identify the difference as the addition of material at the original place of the hole and removal of material from the new place of the hole [3].

Semantic representation of the differences between part models is a difficult task due to the variety of modeling solutions used across industries, the non-uniqueness of modeling sequences and the use of low-level information, e.g. STEP files, in engineering communications. Various modeling solutions and different versions of each of those modeling solutions are used for the same application domain in different industries, although standardization of the data exchange of 3D CAD models has already been proposed [4].

Because of the non-uniqueness of modeling operations sequences, even if the same modeling solution is used to model the same part, models of the same part could be identified as being different. Even if the data structure differences between various modeling solutions and their versions, as well as the non-uniqueness of modeling operations sequences were not hindrances to conducting MDI on native models, identifying the differences between models based on modeling operations would not necessarily express engineering semantics.

Considering these drawbacks of an MDI solution based on native CAD models or B-rep models, it seems inevitable to take measures to elevate the level of information that is readily available from CAD models. For this purpose, automated feature recognition has been researched comprehensively to elevate the level of information of CAD models [5]. Feature models contain features that represent high-level engineering semantics. An MDI method based on feature models created by an automated feature recognition solution would avoid any non-uniqueness of the native CAD models resulting from solution variances and from modelling sequence variances.

This work proposes an MDI method that represents the differences based on engineering semantics through features. The relevant previous works are reviewed in the following section. Next, the proposed method is detailed in steps that describe how to perform pose registration and difference identification. CAD models of real-world parts are used to illustrate the proposed method and its steps. Different aspects of difference identification are elaborated in order to paint a clear picture of the problem and the solution. Lastly, the method is illustrated by comparing real-world examples and identifying their differences.

2   RELATED LITERATURE AND POSITIONING OF PROPOSAL

The method proposed in this study involves pose registration and feature-based 3D model comparison, as well as their implementation for aerospace sheet metal parts. Therefore, the following short subsections review the pertinent fundamental literature.

2.1   Pose Registration

Comparing 3D CAD models requires either matching the size and orientation of the models [6-8] or utilizing size- and orientation-insensitive comparison methods. Granted that using a size- and orientation-insensitive comparison method is incongruous to a comparison method that aims at proposing a semantic MDI, we focus on presenting literature relevant to the former approach.

The process of matching the orientation of the models is also referred to as "pose registration" or "pose estimation" [6]. Pose registration processes generally include the translation of 3D CAD models so that their center of mass shifts to the coordinate origin and then using Principal Component Analysis (PCA) to determine their canonical coordinate system axes [6, 8, 9]. The Iterative Closest Point (ICP) algorithm is another method, introduced by Besl and McKay, to address the geometry alignment problems of point clouds to a reference CAD model, applicable to inspection [10]. For similar problems, Pottmann et al. provide another method which is based on instantaneous kinematics and on the geometry of the squared distance function of surfaces [11].

Tarbox et al. proposed a pose registration method of octree 3D CAD models in which a gross registration estimates a pose transformation and then a fine registration refines the relative pose of the compared CAD models vis-à-vis the objective function [12]. While our proposal does not use the method proposed by Tarbox et al. [12], it does borrow that method's division of registration into stages. Eventually, all of the aforementioned pose registration methods normalize the orientation of the 3D CAD models regardless of their feature structure. In their survey paper, Yang et al. reports pose registration as a step before feature extraction in a typical framework of content-based 3D CAD model retrieval [7]. In contrast, the pose registration method of our proposal is considered as a step after feature extraction.

2.2   Feature-based Comparison

The literature in the area of feature-based comparison for the purpose of difference identification is quite limited. In one of the few works, Smit et al. presented a way to describe the difference between two models in terms of features [13]. They concluded that the problem is resolvable only if the features between models could be mapped. This conclusion is very significant and will be discussed in the method proposed here.

In contrast, the literature in the area of feature-based comparison for the purpose of similarity assessment [14-16] or similar model retrieval is quite rich. Similarity and difference are two sides of the same coin; however, there is a delicate point to be highlighted. Similarity (representation of commonality of two objects) is commutative, while difference (representation of objects subtraction from each other) is not commutative. This means that the similarity of a to b is equal to the similarity of b to a, but the difference of a from b is not equal to the difference of b from a. In addition, identifying the similarities or differences of two CAD models could be prioritized differently according to the scenario. For example, similarity assessment would be a priority in part family formation. On the other hand, in remeshing 3D CAD models, finding differences is more important.

Originally, Cicirello and Regli proposed a new method for implementing solid model comparison by machining features for model retrieval [17, 18]. The machining features were used to represent the solid models in Undirected Model Dependence Graphs. Excluding the directionality from their graph representation resulted in the elimination of feature order, also known as the precedence constraint. Meanwhile, Li et al. proposed a method for reusing 3D CAD models through Knowledge-Driven Dependency Graph Partitioning, in which the precedence constraint is preserved [19]. It is worth noting that the order in which features are created in the native 3D CAD model was used to

extract feature precedence, rather than a hierarchical notion. Even though the interdependencies (relationships) of the features are completely conveyed through the proposed method, being dependent upon CAD operations to extract features and their interdependencies limits their proposal's application. Chu et al. proposed the integration of form-feature adjacency graphs and topology graphs to improve similar model retrieval accuracy [20]. They suggest that if such measures fail to discriminate the best match for the queried model, D2 shape distributions would be used to rank the results of the search based on form features and topology.

2.3 Feature Definition and Description

Our previous work proposed a definition of a feature as: a portion of a geometry model that is significant in at least one of the phases of the product's lifecycle and can be described by its attributes [21]. The attributes of a feature include its geometry, its relationship to other features and its parameters. For example, the geometry of a hole is its faces, and its relation to its parent feature is represented by the edges connecting it to its parent feature. The parameters of features are from relatively lower- to higher-levels of abstraction. Inspired by the work of Brunetti and Grimm [22], who proposed a model of representation layers for feature-based shape data, we propose that feature parameters be categorized as dimensions, dimensional constraints, geometric constraints and representative elements. The representative elements of a feature are of the lowest level of abstraction, as they are basically geometric or topological elements. Dimensions and geometric constraints are of relatively higher-level of abstraction, while dimensional constraints are of the highest-level of abstraction. Figure 1(a) displays a graphic way to organize the information of a feature and its attributes with the help of illustrations (Figures 1(b) to (d)) of an aerospace sheet metal part.

Given that the parameters of a model are considered significantly relevant to the engineering knowledge of a part [22], their detailed explanation helps in understanding their application in this work. Dimensions constrain the geometry or the relative positions of shape elements, and dimensional constraints constrain dimensions through equations or inequations. For example, the diameter of a hole or the radius of a corner constrain their shape, and a dimensional constraint relates these values according to design rules. Geometric constraints relate the geometries of shape elements. For example, parallelism relates the geometry of two planes to each other. The representative topological or geometric elements are parts of feature definitions that are used to calculate their geometry. For example, the plane or surface that a flange rests on is a geometric element that is used to calculate the geometry of that flange.

A feature's relationships to other features are its semantic links to them. We propose that the relationships of a feature to other features are formed by a set of topological elements connecting their geometry together. These relationships reveal the feature structure of geometry models. Such feature structures, which are dependent on the topological elements, are immune to the non-uniqueness of modeling operations' sequences.

Parent-child relationships have been used in previous works to rationalize relationships between features in sheet metal parts [23, 24]. Parent-child relationships are limited to refer exclusively to the relationship between an item of the hierarchy with another one at one level higher or lower. Because the parent-child relationships between features are not sufficient to describe the multi-level hierarchy of features in 3D CAD models, we introduce some helpful nomenclature. Here, a feature that depends on another feature, directly or indirectly, is its *subordinate feature*, and the feature it is dependent upon, directly or indirectly, is its *superior feature*. A feature could be subordinate to its superior feature and at the same time superior to its subordinate feature. An *immediate* subordinate or superior feature is a feature at one level lower or higher in the hierarchy, respectively. An extended subordinate or superior feature is a feature at more than one level lower or higher in the hierarchy. Hierarch is a feature of highest rank, which does not have a superior feature in the feature structure. Two features are peers if they are at the same rank in the hierarchy and from the same branch (their superior features to the hierarch are in the same order).
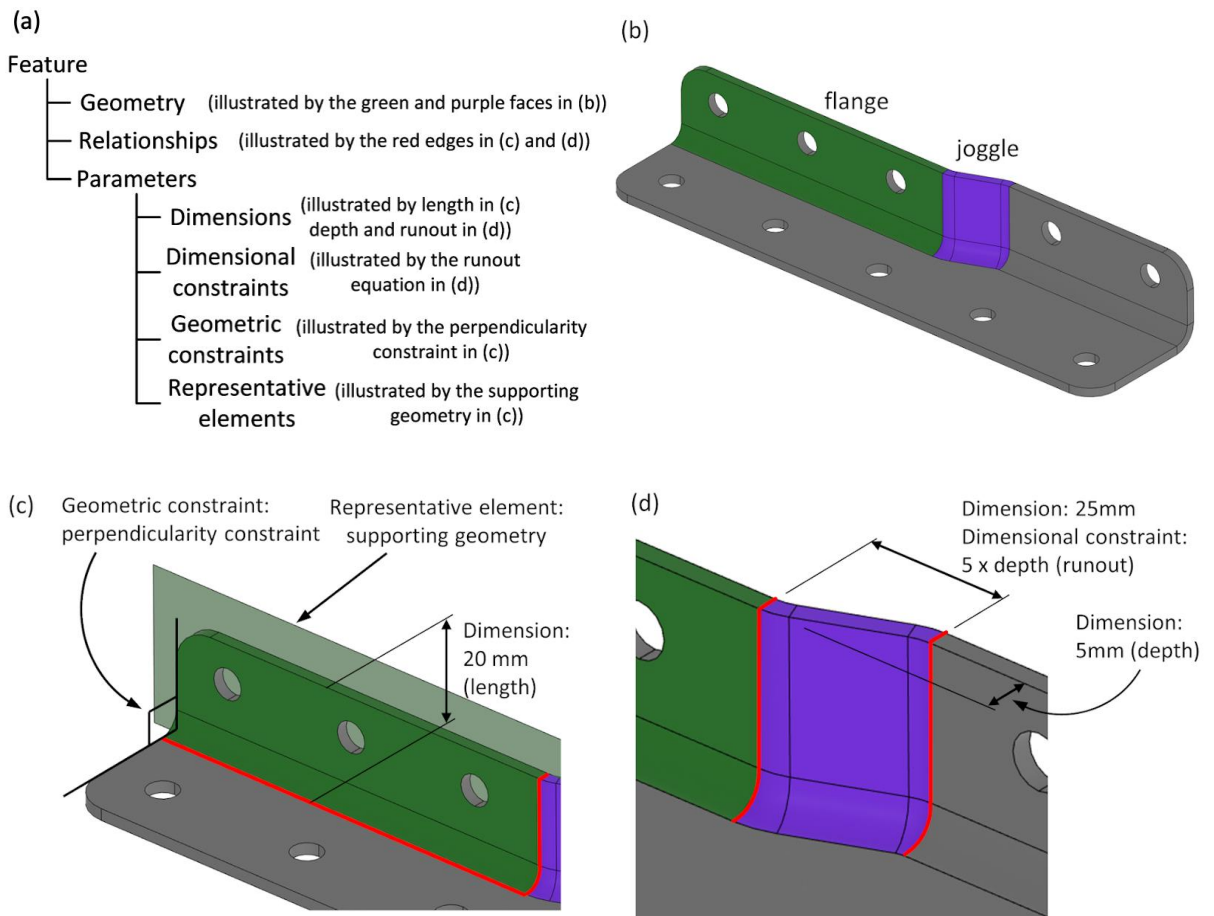
Figure 1: A representation of feature information and the illustration of its attributes.

2.4   Aerospace Sheet Metal Sample Parts

Contemporary feature-based modeling solutions are specialized for specific applications, such as aerospace sheet metal part design. Contrarily, the MDI solutions and methods are not nearly as specialized [3, 25]; however, they could take advantage of being approached with specific applications in mind. Given that in a previous paper we proposed an automated feature recognition method for Aerospace Sheet Metal (ASM) parts, we used the same domain of application to propose and illustrate our MDI method in this work.

The features in ASM parts included in this study were observed by studying the design guidelines and 168 diverse structural sheet metal parts of aircraft structure. A structural system is comprised of a thin-skinned shell which is stiffened by longitudinal stringers supported by transverse frames to form a semi-monocoque structure [26]. The parts that we studied for this paper were all produced by brake-forming or hydro-forming, and thus skin panels and stringers were omitted. Brake-formed and hydro-formed parts may include frames, bulkheads, passenger and cargo floor structures [26] and cockpit components.

The generic features of the ASM parts were listed as *web*, *trim features* (*cutout*, *hole*, *stringer cutout*, *bend relief* and *corner*) and *deformation feature* (*lightening cutout*, *lightening hole*, *flange*, *lip*, *joggle*, *twin joggle*, *deformed flange*, *deformed web* and *bead*) in our previous paper [21]. The previous taxonomy of features of the ASM parts was based on the manufacturing viewpoint. In this work, however, the focus is on functionality and design intent, and so holes are divided into *attachment holes* and *tooling holes*, while flanges are divided into *stiffening flanges* and *attachment flanges*. Figure 2 illustrates examples of all these features in actual ASM parts.
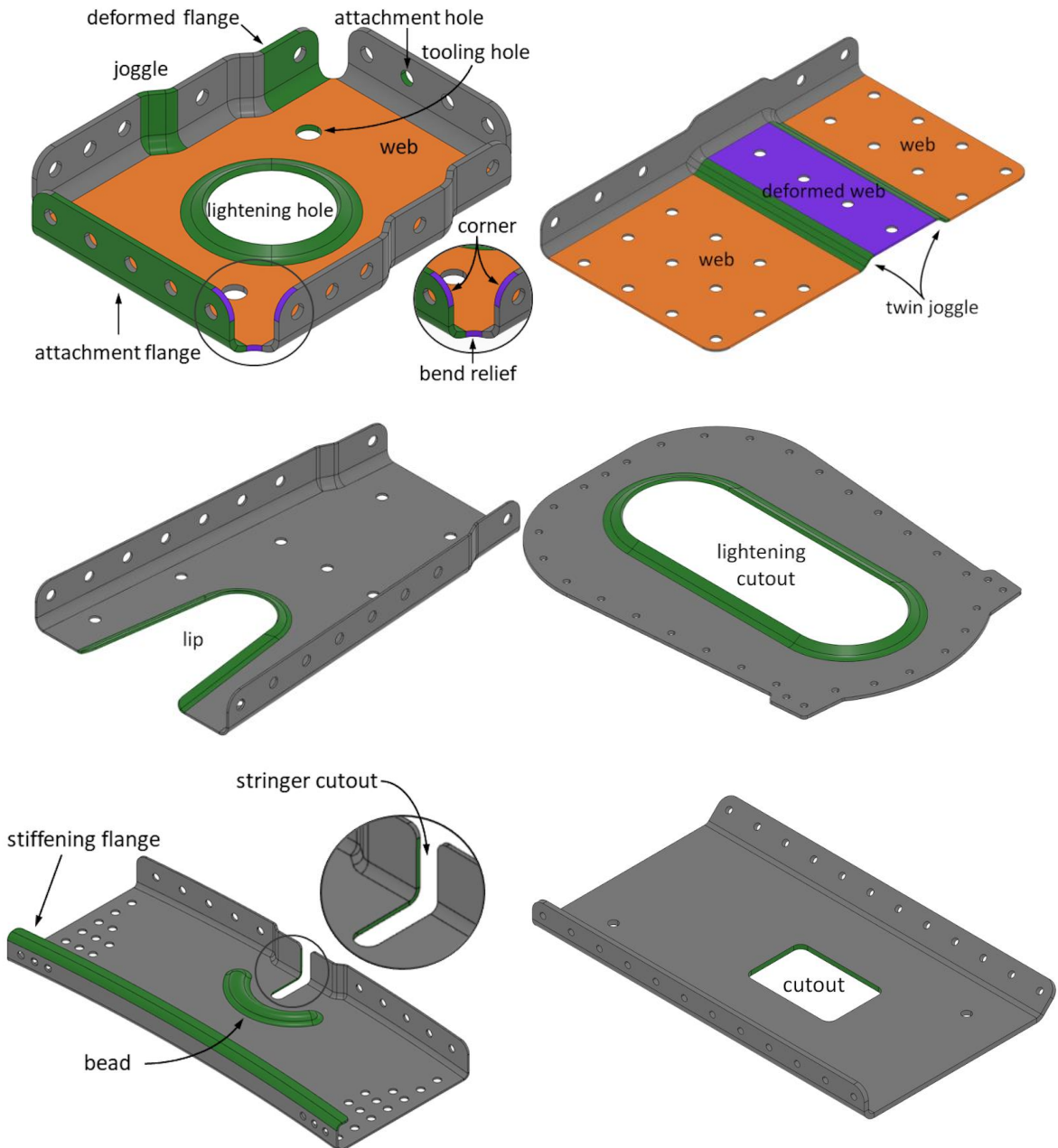

Figure 2: Examples of features in real-world ASM parts [21].

Attachment and stiffening flanges can be subcategorized according to their class: planar or curved, immediate or return, single or conjoint, and closed, perpendicular or open depending on the angle between a flange and its superior feature. The examples illustrated in Figure 3 show some variations of attachment flanges and stiffening flanges that occur in real-world part designs.
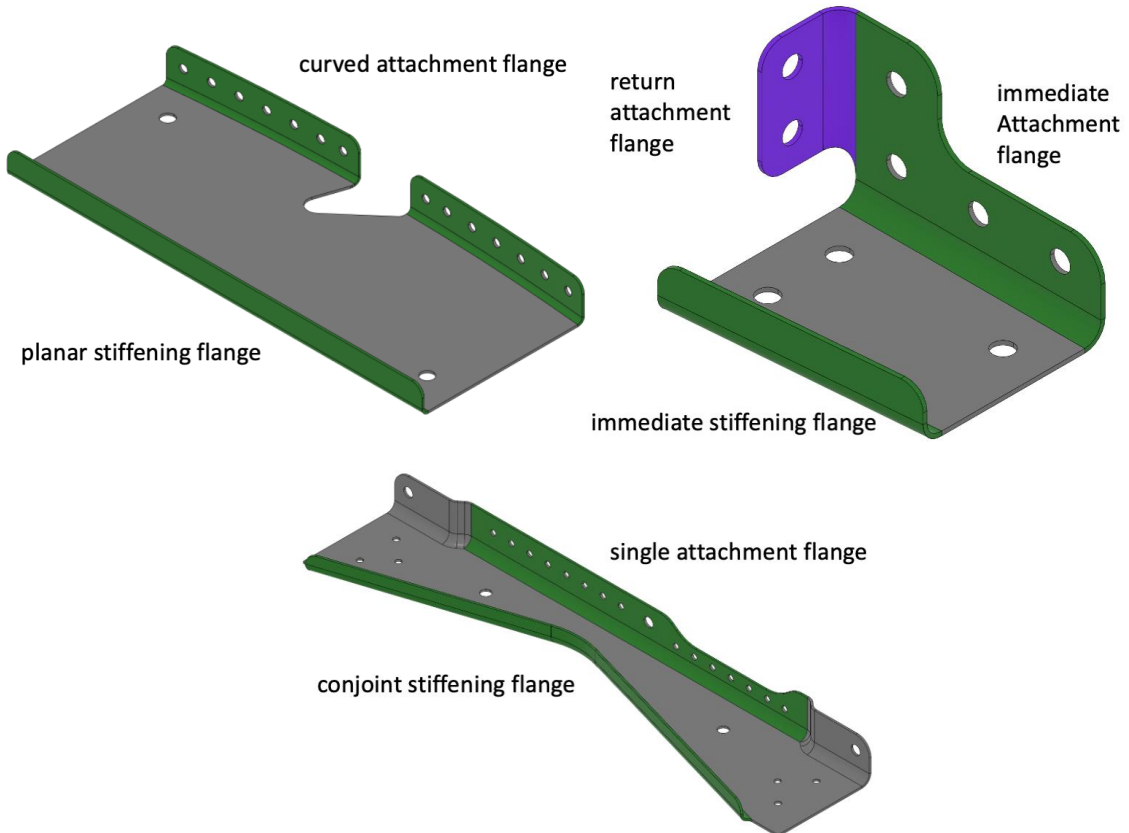

Figure 3: Variations of attachment flanges and stiffening flanges that occur in real-world part designs.

In this work, the taxonomy is adapted to meet the needs of semantic MDI. The ASM features are categorized into _base feature_, _contact features_ and _refinement features_. In many domains of feature-based 3D CAD modeling, there is a base feature that the rest of the features are built upon or are modifying. Here, the web is the base feature in brake- and hydro-formed ASM parts. The contact features are the features, other than the web, that are involved in either parts' interfacing or in facilitating the interfacing, so as to provide sound contact between interacting parts. These include the _attachment flange_, _joggle_, _twin joggle_, _deformed flange_, _deformed web_ and _attachment hole_. Contact features have specific functions like attachment (fulfilled by attachment flanges, deformed flanges, deformed webs or attachment holes) and adjustment (fulfilled by joggles or twin joggles).

The refinement features are non-contact features that are created for refinement purposes such as weight saving, or for allowing pass-through, stiffening, or manufacturing purposes, or a combination of these purposes. Refinement features include _corner_, _bend relief_, _lightening hole_, _lightening cutout_, _cutout_, _stringer cutout_, _lip_, _bead_, _stiffening flange_ and _tooling hole_. It is worth

noting that using attachment holes on the web with a diameter smaller than the diameter of a standard tooling hole for tooling purposes, if required, is a common practice. Figure 4 illustrates the feature taxonomy of the studied ASM parts in terms of their functions and purposes.
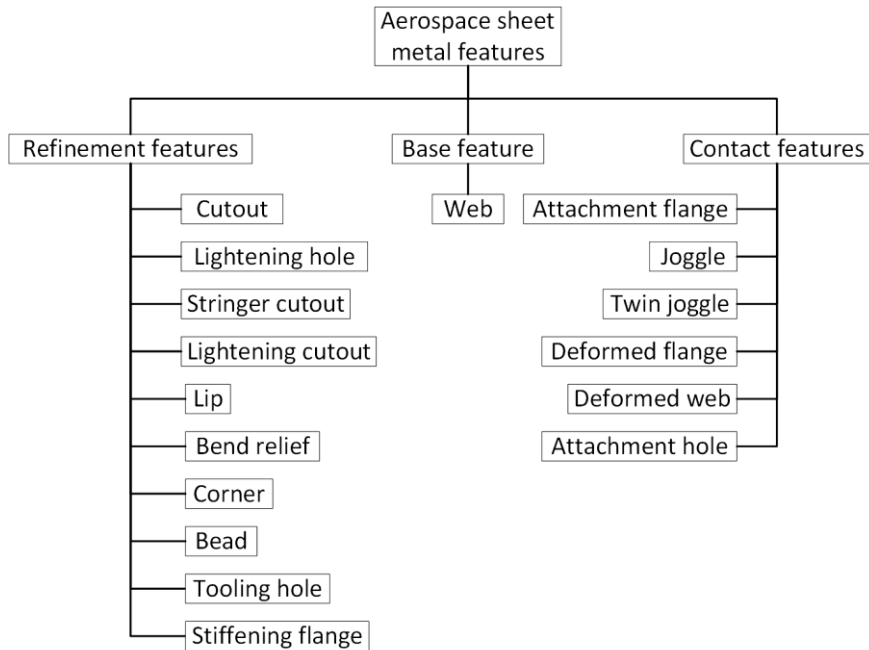

Figure 4: The taxonomy of feature types in the studied ASM parts in terms of their functions and purposes.

To clarify the representation of ASM features, the web, an attachment flange, a corner, and a lightening hole of an actual ASM part are illustrated in detail in Figure 5. Figure 5 (a) shows a 3D CAD model of the part and its features, which are colored. The geometry of the features is formed by the B-rep elements (their faces), some of which are shown separately in Figure 5 (b). The relationships between each feature and its subordinate or superior feature is formed by the edges shared between their faces, indicated in Figure 5 (b) with arrows pointing to the superior feature. In Figure 5 (c), the lower-level parameters of these features are illustrated and their higher-level parameters are indicated.
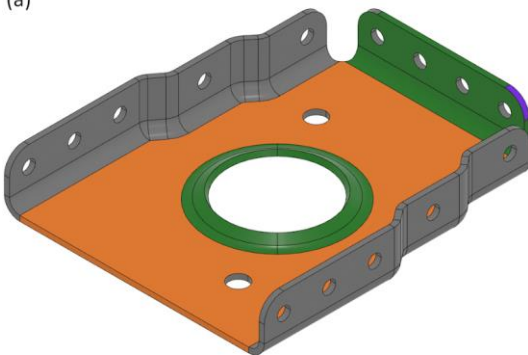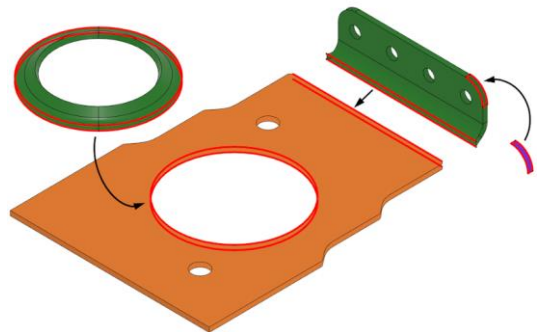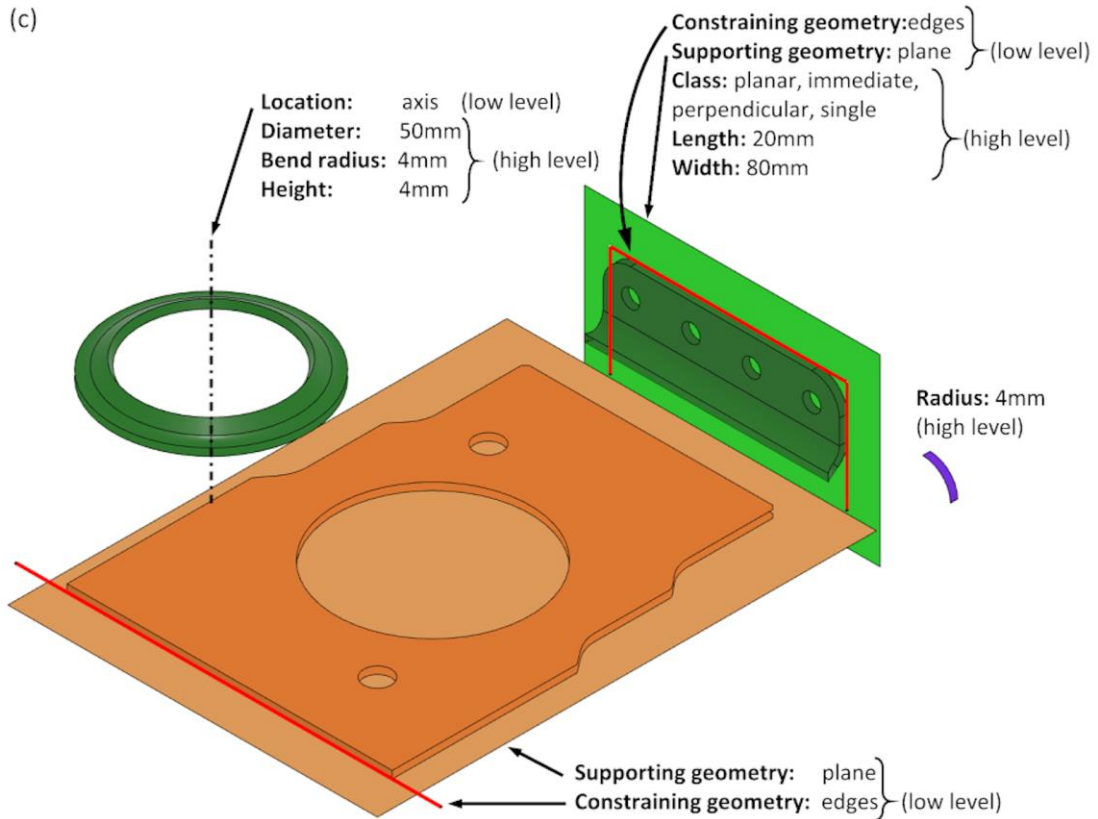
Figure 5: Representation of the web, an attachment flange, a lightening hole and a corner of an actual ASM part according to the feature definition.

3 PROPOSED METHOD

The proposed feature-based model difference identification method is divided into two stages: pose registration and difference identification. The difference identification stage can in turn be divided into two main steps: 1) *commonality segregation* and 2) *difference identification* and *difference characterization*. Figure 6 summarizes the proposed method; some steps taken in the example illustrated in section 3.3 are color coded to match the colors of the pertinent shape elements in Figures 9 and 10.

Before detailing the pose registration and difference identification methods, it is important to explain that these methods are based on an explicit representation of the parts in terms of their features; feature models. These feature models could be created in a feature recognition preprocessing stage [27], which is excluded from the scope of this paper.

3.1 Pose Registration

One of the gaps that this work aims to address is registering the compared 3D CAD models semantically, here called *semantic registration*. We assume that all the features that compose a part are purposeful. This provides the opportunity to semantically register feature-based 3D CAD models according to the unique purpose of the features in our specific domains of application. Linking design intent, parts' functionality, and features have been the subject of other studies, e.g., for robust CAD modeling [28, 29].
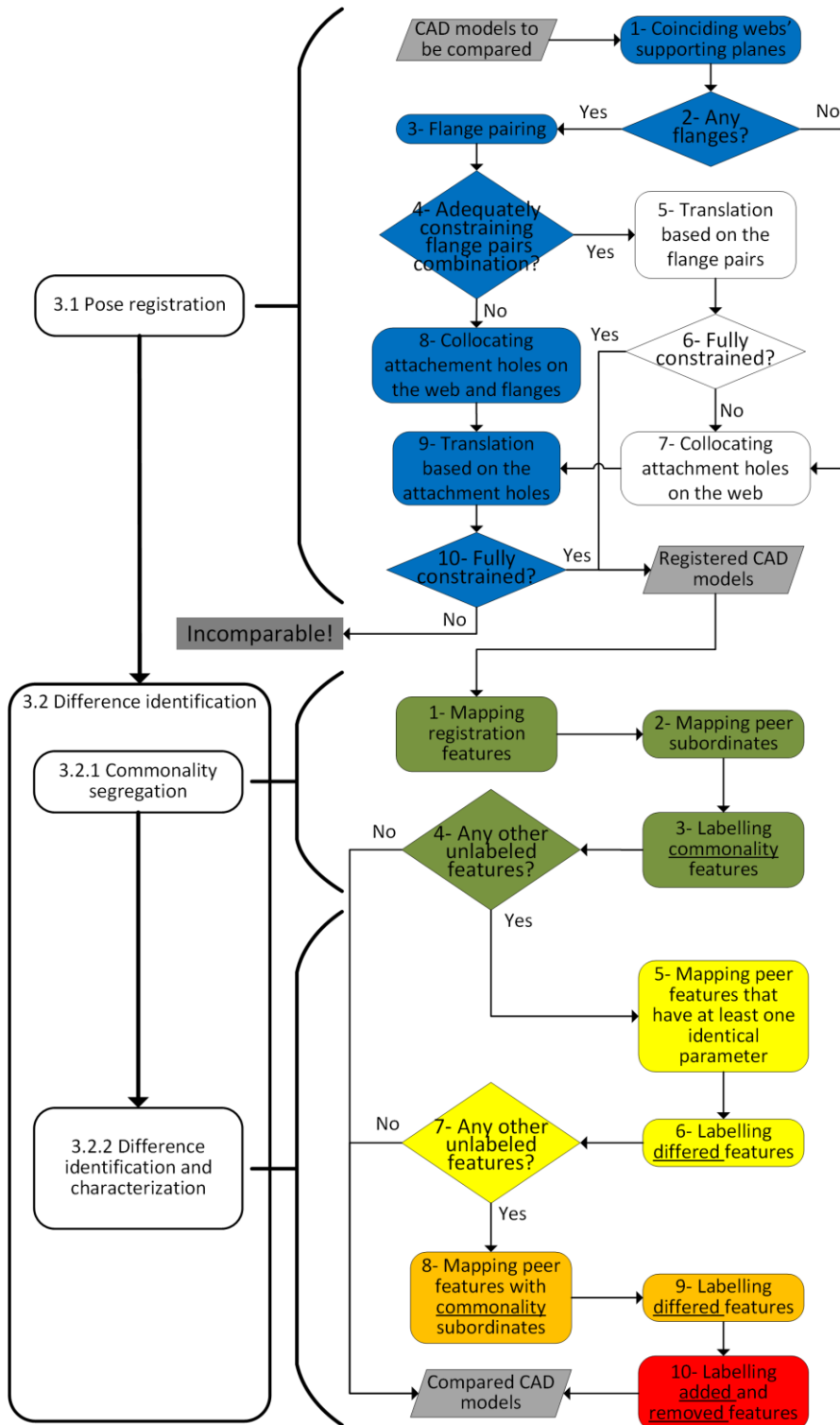
Figure 6: Overview of the proposed pose registration and difference identification stages.

In ASM parts, functionality and features are intertwined into design practices. With a focus on the design practices of ASM parts, the 168 sample parts mentioned above were investigated, and interfacing and attachment were found to be the indispensable functionality of all ASM parts (as explained in section 2.4). Therefore, the features vital to interfacing and attachment are considered of semantic significance in order to propose a method for semantic registration. For example, the frames, bulkheads, passengers and cargo floor structures are formed by assembling ASM parts together, which makes features with interfacing and attachment functionality fundamental to part design.

The web is the base feature; the rest of the features of parts are formed directly or indirectly based upon it. As a result, the semantic registration of two ASM parts must involve pairing their webs. The notion of using base features to semantically pair feature-based 3D CAD models of parts is applicable to different domains of application, e.g. machined parts, non-aerospace sheet metal parts, composite parts, etc.

In addition to using the base feature, attachment flanges (essential to the interfacing of ASM parts) and/or attachment holes (necessary for attachments) should also be used in semantic registration. Attachment flanges are given precedence to attachment holes in their use for semantic registration. Nevertheless, in the absence of attachment flanges, or when they are not constraining enough to register the two 3D CAD models, attachment holes are taken into account.

According to the above-mentioned premises, we propose the following steps, which are illustrated by the example in Figure 7 (a):

1- *Coinciding webs' supporting plane:* Translate the target model so that the supporting plane of its web coincides with that of the reference model, as shown in Figure 7 (b).

2- *Checking for the presence of any attachment flanges:* Check if the two compared models have attachment flanges; if not, skip to step 7.

3- *Flange pairing:* Pair the attachment flanges of the two compared models according to their classes, as shown in scenario A and scenario B in Figure 7 (c). An attachment flange in each of the models could be paired simultaneously with one or more of the attachment flanges of the other model if their classes agree, as in the example here.

4- *Checking for the presence of an adequately constraining combination of flange pairs:* Check if there could be a single combination of attachment flange pairs that enables the superposing of all or of a plurality of the paired attachment flanges simultaneously so that their supporting geometries coincide. It is possible that there are more than one attachment flange pairs that enable the superposing of all or of an equal plurality of the paired attachment flanges simultaneously (illustrated by Figures 7 (c) and (d)). If there is not a single combination of the attachment flange pairs that could enable superposing all or a plurality of them, skip to step 8.

5- *Translation based on flange pairs:* Calculate the translation to superpose the selected attachment flange pairs and translate the target model according to the calculated translation, as shown in Figure 7 (e).

6- *Checking if the parts are fully constrained:* Evaluate if the models are fully constrained to each other (so they have no relative degree of freedom). If the models are not fully constrained to each other, continue with the next steps, otherwise, the models are semantically pose registered. Being fully constrained could be evaluated by verifying that the mapped attachment flanges between the models are greater than one and are not only parallel planar attachment flanges or concentric curved attachment flanges.

7- *Collocating attachment holes on the webs:* Identify the largest set of attachment holes on the webs that could collocate without violating the previous attachment flange superposition and skip to step 9. It should be noted that this step is used in cases where there is no flange on a part, or when flange pairing did not suffice to fully register the models.

8- *Collocating attachment holes on the webs and flanges:* Identify any of the combinations of attachment flange pairs that enables the largest set of attachment holes on the webs to collocate. If required, identify the combinations of attachment flange pairs that also enables collocation of the largest set of attachment holes on the attachment flanges themselves. Figures (f) and (g) illustrate how collocating attachment holes on the web and the attachment flanges themselves could be determinant in selecting the attachment flanges pair combination.

9- *Translation based on attachment holes:* Calculate the translation to collocate the set of attachment holes and translate the target model according to the calculated translation.

10- *Checking if the parts are fully constrained:* Evaluate if the models are fully constrained to each other (so they have no relative degree of freedom). If the models are not fully constrained to each other, they are not viable to be registered based on their web, attachment holes and attachment flanges (the features that are fundamental to the functionality of aerospace sheet metal parts), so they are considered incomparable due to a lack of adequate functional similarities.

The proposed semantic registration steps only include translation and rotation transformations and is therefore rigid. Before proceeding to the difference identification stage of this work, it is relevant to discuss the comparability of the models. Although an MDI method per se does not need to include verifying an adequate commonality condition, such condition is a prerequisite that needs to be stipulated. The studied ASM parts are designed for the purpose of structuring the fuselage and cockpit to be adequately strong and to provide a frame to which to assemble other systems. The web, attachment holes and attachment flanges are the main features to enable the parts' functionality. While what constitutes adequate commonality could be perceived subjectively, here we suggest that the presence of enough of the features fundamental to the parts' basic functionality is essential to consider two parts comparable.

Identifying the differences between two parts is meaningful so long as the parts have adequate commonality. Comparing two parts without enough functional commonality would allow futile difference identification results. Interestingly, if the adequate commonality condition is based on their constituent features, and the constituent features are considered uniquely purposeful, the comparison scenarios must be restricted to parts whose design purposes are adequately similar.
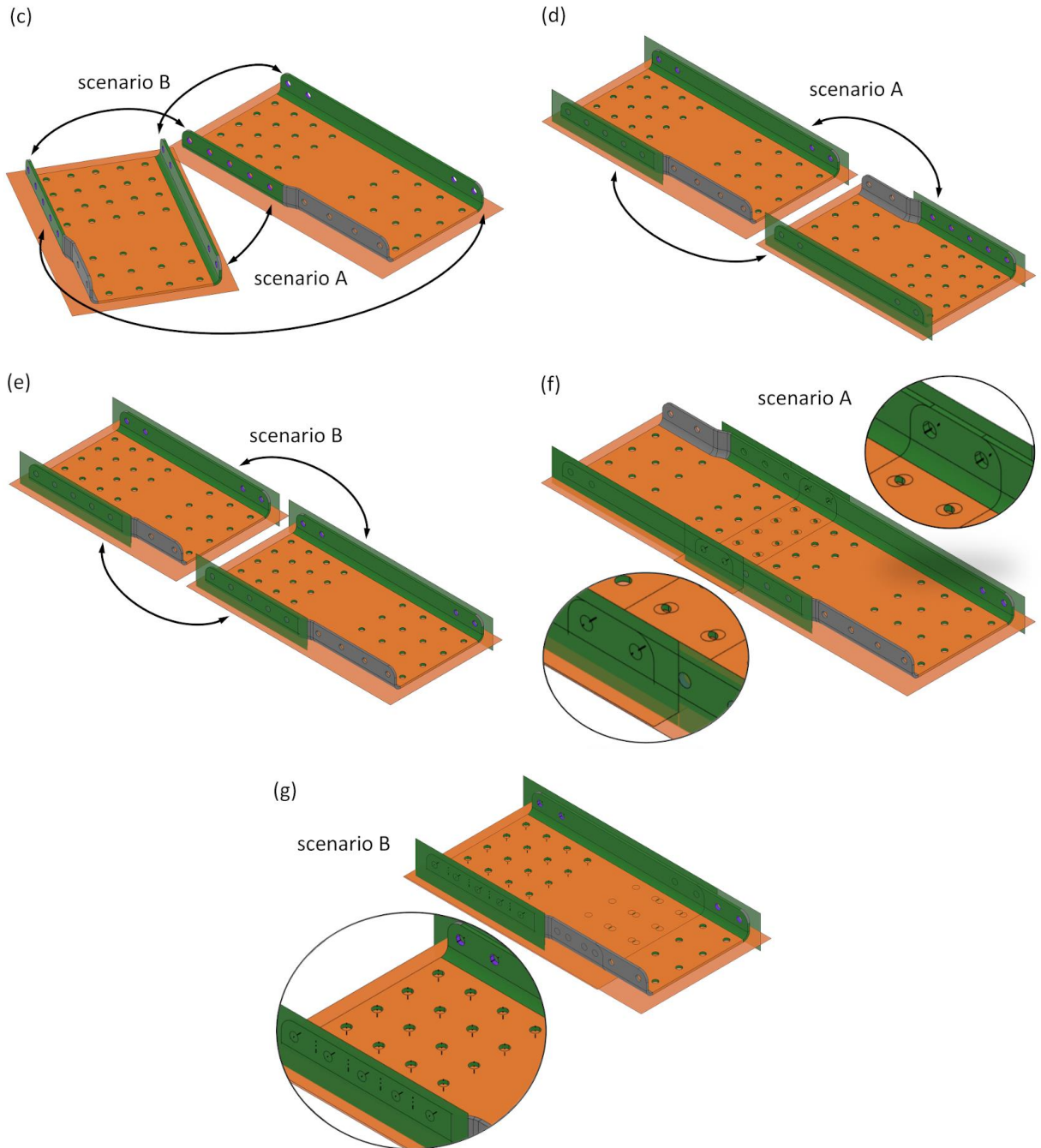

(a) initial relative pose in 3D space

(b)
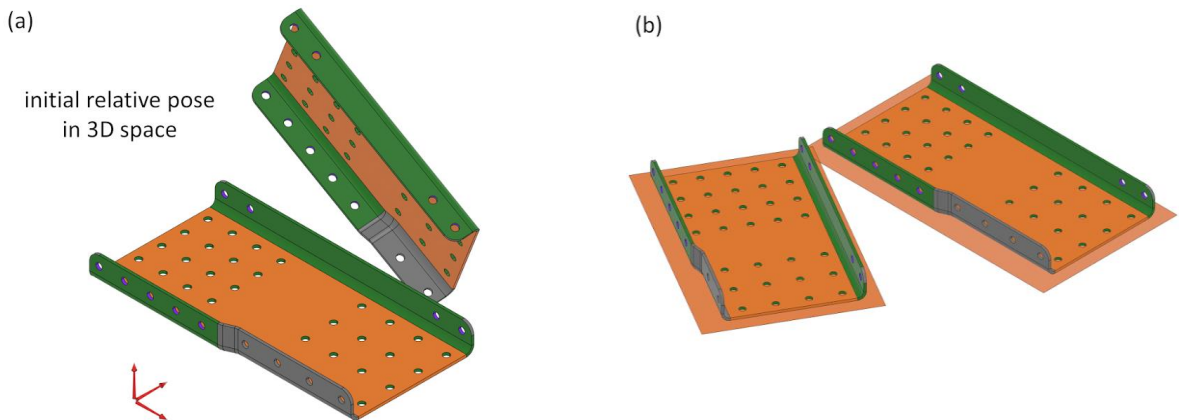
Figure 7: Illustration of the proposed semantic registration method through an example.

3.2 Difference Identification

In a very insightful paper, Viswanathan et al. asked a question that is pivotal to this work: "How can the dimensions and positions of geometric features in the two given components be

compared?" [30]. Although their work proposed a measure for calculating a commonality value based on dimensions and position, their pair-wise comparison viewpoint matches perfectly with the scope of this work. They also proposed using an automated feature recognition method rather than extracting features from modelling operations in the native 3D CAD models. In response to the question asked by Viswanathan et al., the parameters of features, which resemble the role of dimensions and positions of geometric features, are involved in the difference identification method proposed here. A feature's high-level parameters include all of its related dimensions, and its low-level parameters constrain its position.

In order to identify differences, comparison is required. However, comparison between any two objects yields both their commonalities and their differences. Excluding the commonalities of two objects from their comparison results effectively identifies their differences. Thus, we propose to begin the difference identification process by a number of initial steps to identify and exclude the commonalities between the feature models (commonality segregation), and then to follow with difference characterization steps to finalize difference identification. While the bottom half of Figure 6 summarizes the steps of the proposed difference identification stage, Figure 8 illustrates these steps in an example.

3.2.1 Commonality segregation

The feature structure of the 3D CAD models – formed by their features, their relationships, and their features' parameters – are used to map features with identical parameters between the compared models (primary mapping). These mapped features form the commonality between the feature models. The commonality segregation steps identify the identical features between the compared models to discard them from the difference identification process.

Figures 8 (a) and (b) displays two fabricated examples of ASM parts with their feature structures. The AHs, AFs, BR, Cs, TJ and DF nodes represent the attachment holes, attachment flanges, bend relief, corners, twin joggle and deformed flange, respectively. Different symbols are used in this figure to distinguish between different hierarchy levels. The following four steps are proposed to complete the commonality segregation:

1- *Mapping registration features:* Map together the webs, attachment flanges and attachment holes that were involved in semantic registration provided that they have identical parameters. Figures 8 (c) and (d) illustrate such mapped features through the blue colored features. Because the compared models can be fully constrained only by coinciding their web's supporting plane and superposing their attachment flanges, they can be registered using only these features. The web and the attachment flanges (AF1 and AF2) are thus mapped at this step.

2- *Mapping peer subordinates:* Search for and map together every two peer (immediate or extended) subordinate features of the same type (e.g. AH9 from the reference model and AH10 from the target model) of the already mapped features, provided that they have identical parameters. Figures 8 (e) and (f) illustrate such mapped features via the green colored features. Note that features like the deformed flanges (DF) and the attachment holes on them (AH12 from the reference model and AH13 from the target model) are peer extended subordinate features of the same type that are located on the already mapped attachment flanges (AF2).

3- *Labeling Commonalities:* Label the mapped features (at steps 1 and 2), e.g. commonality, to distinguish them from the unmapped features.

4- *Checking for the presence of any remaining unlabeled features:* Check if there are any unlabeled features and take them to the next stage. If all features are already labeled, the models' comparison is over, and their difference is an empty set of features.

3.2.2 Difference identification and characterization

Before continuing to the difference identification and characterization stage, we need to elaborate on the possible differences between compared 3D CAD models in terms of their features.

Difference in terms of features can be identified as added, removed or differed features. Differed features are features that are partially similar or partially different. A prime challenge in difference identification is distinguishing differed features from added and removed features. If no differed feature is identified, the differences between the compared 3D CAD models are inevitably identified as removed features from the reference model or as added features to the target model.

To identify all the differed features, we propose a secondary mapping process that is not restricted to features with identical parameters. The following steps, except for step 10, are proposed to complete the secondary mapping:
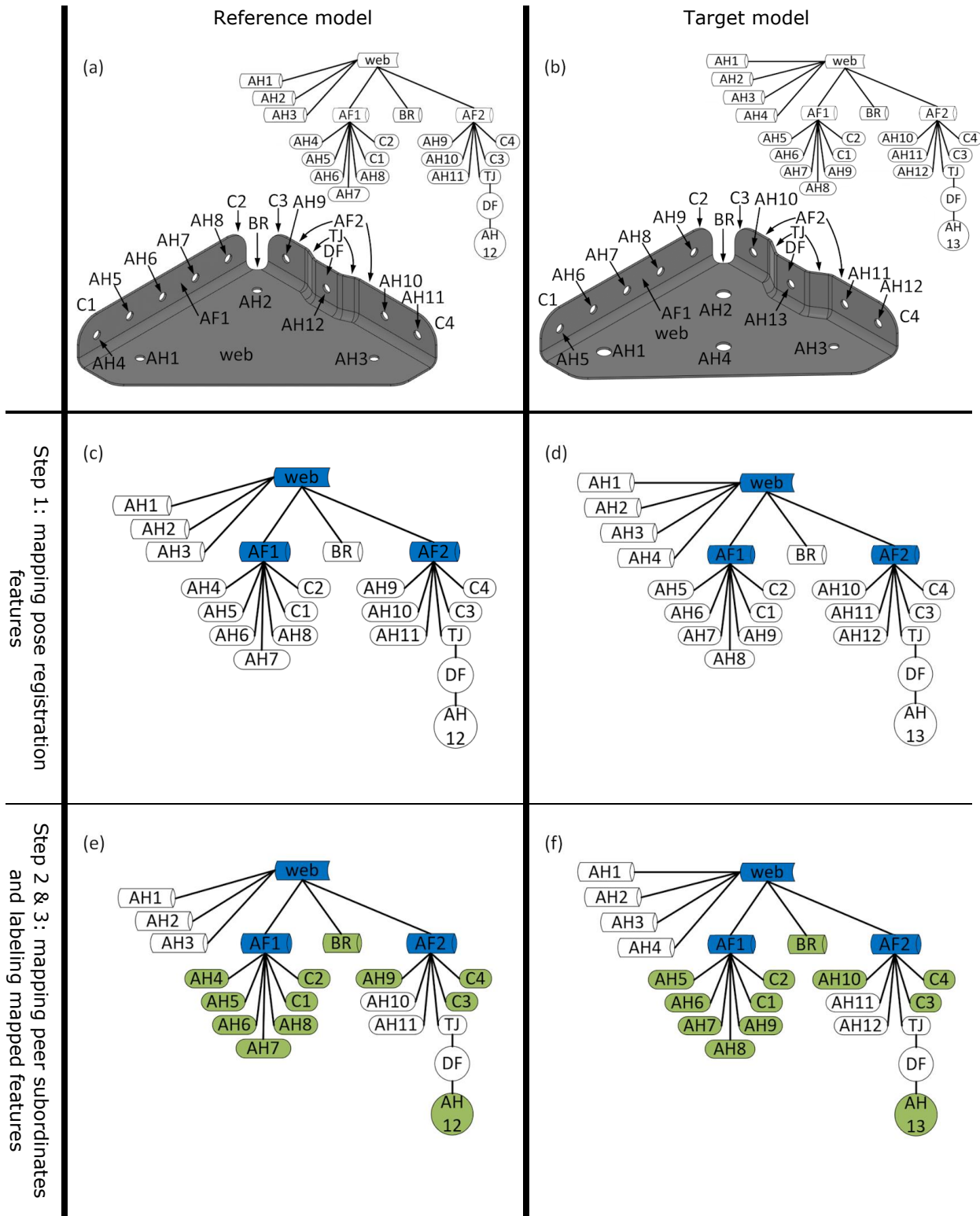
5- *Mapping peer features with at least one identical parameter:* Search for and map together every two peer features of the same type that are unlabeled, provided that they have at least one identical parameter. If there are multiple mapping possibilities, prioritize mapping together the features with the greatest number of identical parameters. Figures 8 (g) and (h) indicate such mapped features in yellow.

6- *Labeling differed features:* Label these mapped features as differed, to distinguish them from the rest of the previously mapped features and the still unmapped features.

7- *Checking for the presence of any other unlabeled features:* Check if there are any unlabeled features and take them to the next stage. If all features are already labeled, this means that the models' comparison is over, and that their difference does not include any added or removed features.

At this point, the remaining unlabeled features are either added or removed features – depending on belonging to a reference or a target part – or differed features. Indeed, subordinate features of an unlabeled feature may already be mapped and labeled, which would contradict with the superior feature to be either an added or a removed feature. For example, all the parameters of a joggle could vary between two parts, without impacting any parameters of its extended subordinate attachment hole (diameter and location of a hole with respect to the part's coordinate system). In all cases, the unlabeled superior features of a pair of already mapped features which are labeled as commonality must be considered as differed. To identify such differed features and to distinguish them from added or removed features, the following steps are proposed:
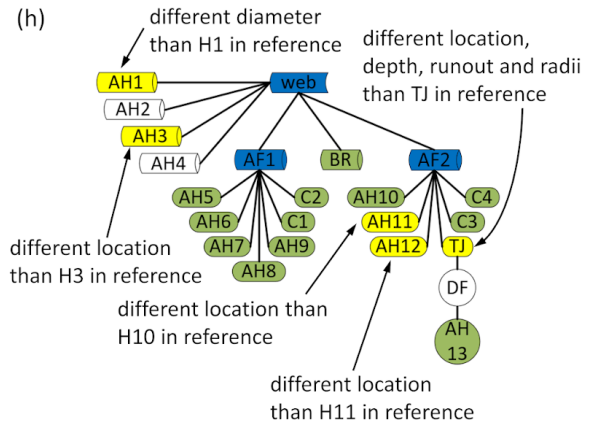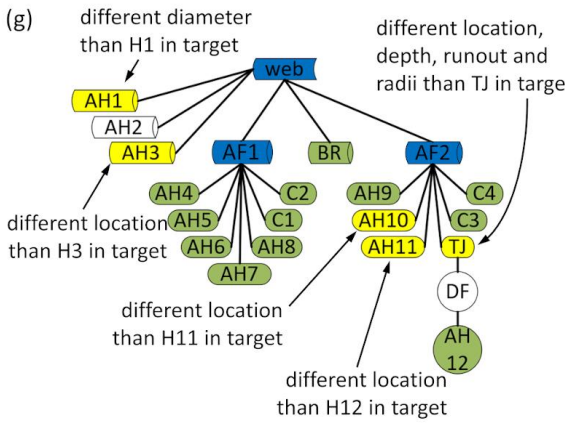
8- *Mapping peer features with commonality subordinates:* Search for and map together every two unlabeled peer features of the same type, provided that they have an immediate or extended subordinate feature labeled as a commonality.

9- *Labeling differed features:* Label these mapped features as differed. The orange colored features (the DFs) in Figures 8 (i) and (j) indicate such differed features. The deformed flanges' subordinate attachment holes have identical parameters and thus show that the DFs, despite not having any identical parameters, serve similar design intent and functionality. Therefore, the DFs are differed features, as opposed to added or removed features.

10- *Labeling added and removed features:* Identify all the remaining unlabeled (still unmapped) features and label them as added if they belong to the target model and removed if they belong to the reference model. Figures 8 (k) and (l) show such mapped features in red.
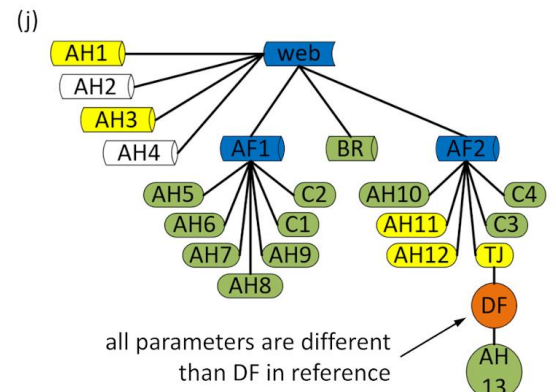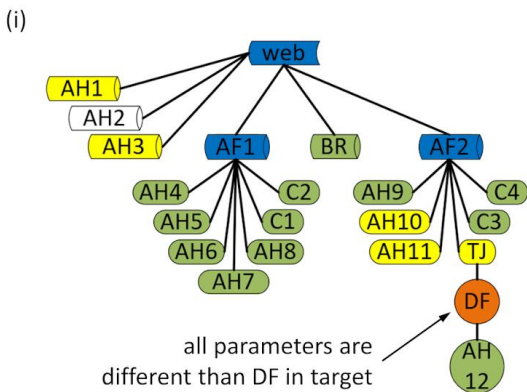
3.3   Illustration of the Proposed Method

Here, we will explain the execution of the proposed method using an example from the samples that were selected from a pool of real parts of a Bombardier DHC-8-102. B-rep models of the sample part and a new version of it were created to recognize their features according to the method explained in our previous work [21]. The B-rep model of the new version of the part is translated to a random position in 3D space. Figures 9 and 10 illustrate the models and the significant steps in identifying their differences.

(g) different diameter than H1 in target

different location, depth, runout and radii than TJ in target

different location than H3 in target

different location than H11 in target

different location than H12 in target

(h) different diameter than H1 in reference

different location, depth, runout and radii than TJ in reference

different location than H3 in reference

different location than H10 in reference

different location than H11 in reference

(i) all parameters are different than DF in target

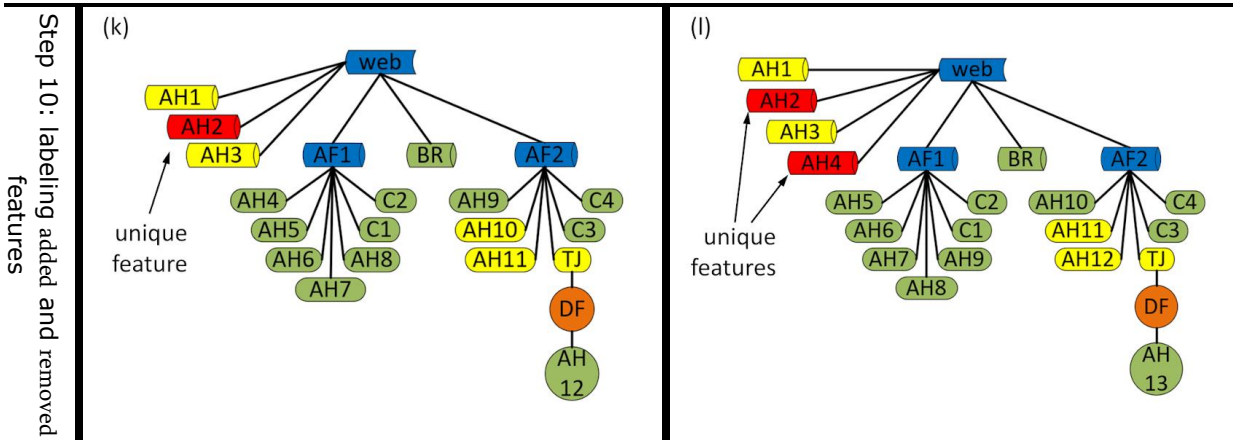(j) all parameters are different than DF in reference

Figure 8: Illustrations of the key steps of the proposed difference identification method.

Figures 9 (a) to (c) illustrate the part, two versions of its 3D CAD model and their features' structures. The four corners that are identical between the models and so are removed from the features' structures to simplify the figures are indicated in Figure 9 (a). In order to register the two 3D CAD models, they are first translated so that their webs' supporting geometries coincide. The parts have attachment flanges that can be used towards semantic registration; however, because the attachment flange pair is not fully constraining, collocating the attachment holes on the attachment flanges is utilized to complete semantic registration. It should be noted that the holes on the web are tooling holes and are not involved in the semantic registration process. Finally, the attachment flange pairs and the collocated attachment holes are used to calculate the translation of the target 3D CAD model. The steps of the semantic registration method taken to semantically register the 3D CAD models are being colored blue in Figure 6. Figures (d) and (e) show the representative elements (the webs' and attachment flanges' supporting geometry in blue and the attachment holes' axes indicated) of the features that were involved in the semantic registration of the target and reference 3D CAD models.
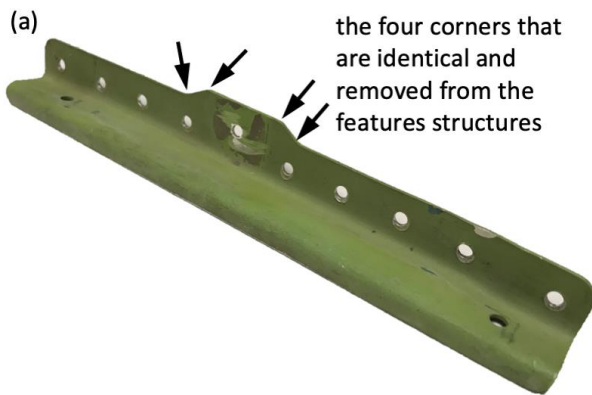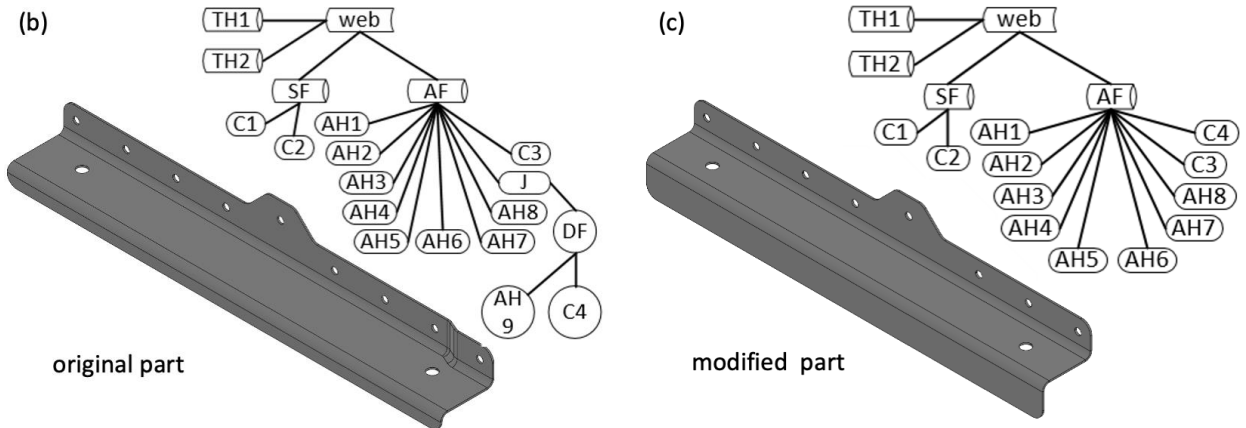
Figure 9: Semantic registration of two versions of a 3D CAD model of an ASM part.

The steps to identify the commonalities and differences between the compared 3D CAD models are color coded in Figure 6 to match the color of the features mapped and labeled in each step. In order to identify and segregate the commonality between the 3D CAD models, the web, attachment flanges and the attachment holes that were used in the semantic registration are evaluated, and those with identical parameters are mapped. Figures 10 (a) and (b) show these features in green and indicate them with arrows. Every other peer subordinate feature of the same type that have identical parameters are identified and mapped (indicated in Figures 10 (c) and (d)). The features that have already been mapped are labeled as (shown in Figures 10 (e) and (f)), and, since not all of the features of the models have been exhausted, it is now time to identify the differences between the 3D CAD models.
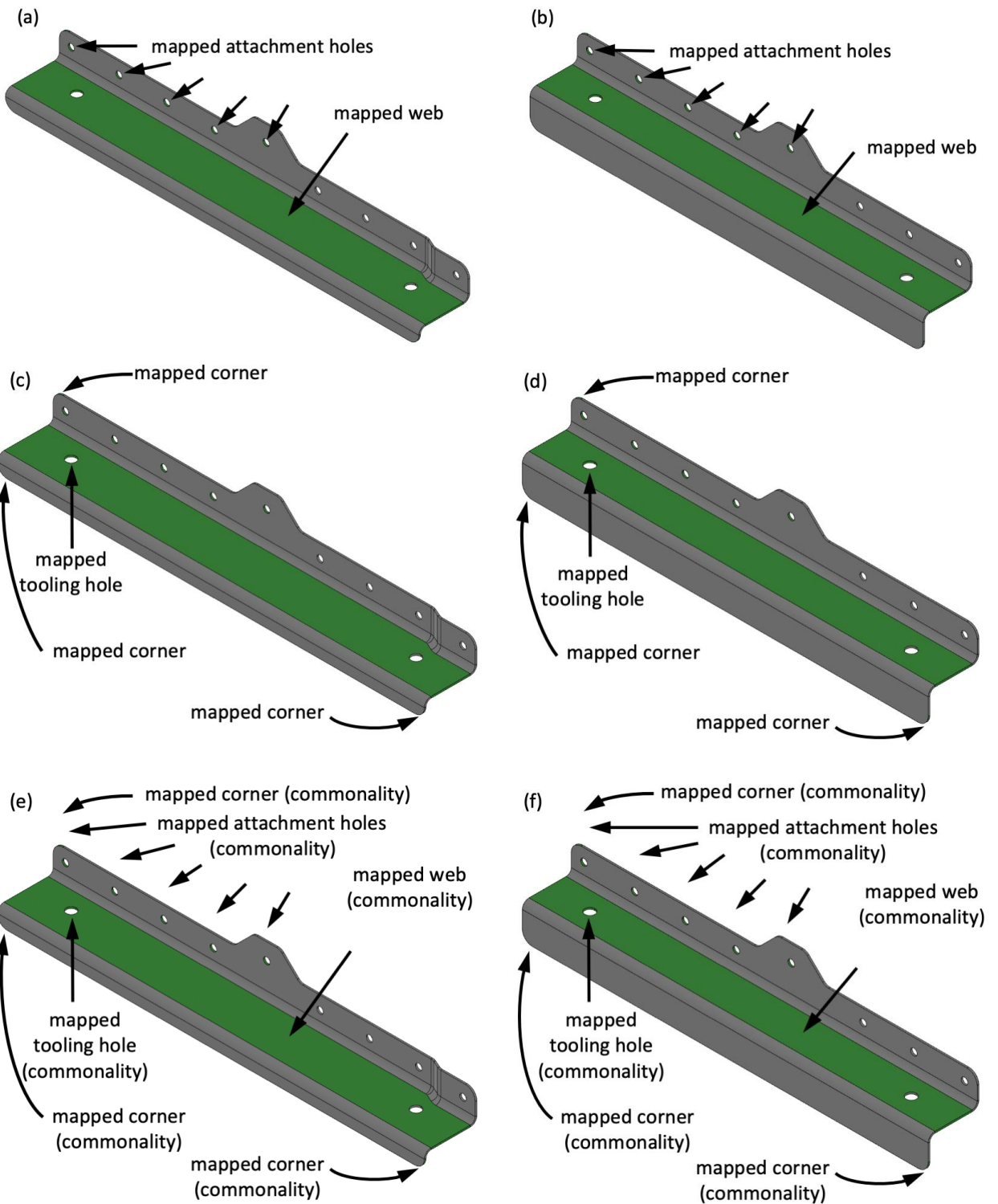
Hence, the peer features of the same type with at least one identical parameter are identified, mapped and labeled as differed. Figures 10 (g) and (h) show these features (the immediate-attachment flange, the attachment holes on the flanges and the tooling hole on the web) in yellow and indicate them with arrows. The attachment flanges are both planar, immediate flanges, and have identical lengths but different widths. The tooling hole and the attachment holes have identical diameters but different locations. The pertinent steps are colored yellow in Figure 6.
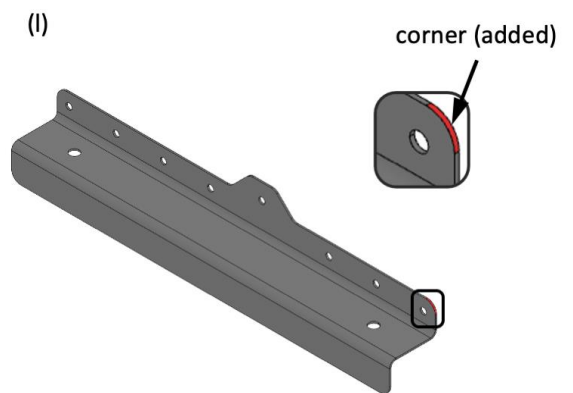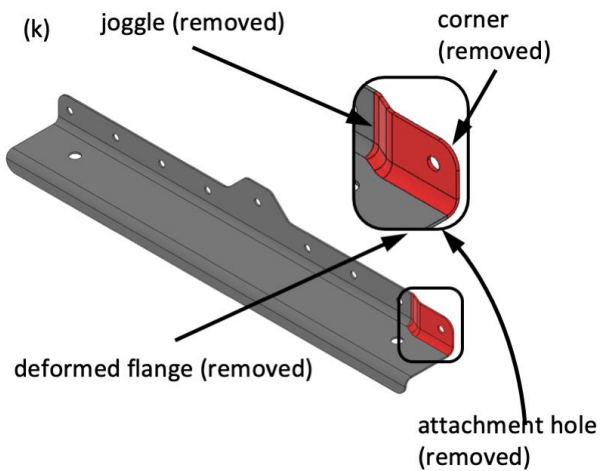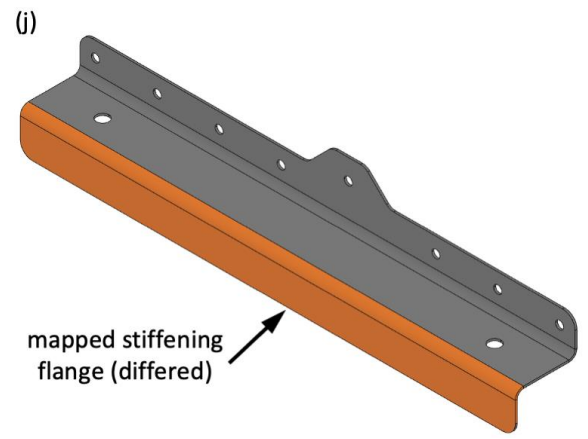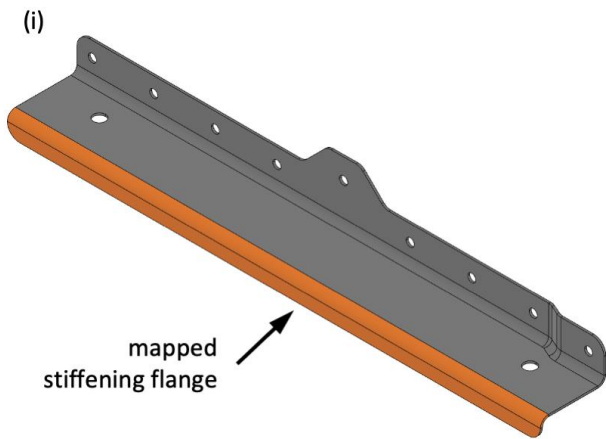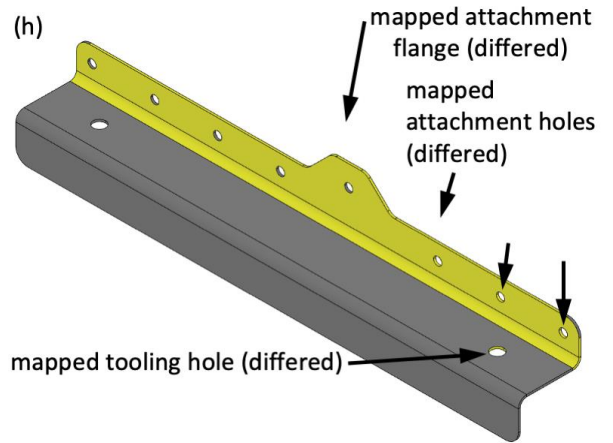
The peer features of the same type that have subordinate features with commonality labels are also identified, mapped and labeled as differed. Figures 10 (i) and (j) show the stiffening flanges (in orange) of both models that have their subordinate commonality corners (indicated in Figures 10 (c) and (d)).

The remaining unlabeled features of the reference 3D CAD model are unique features and therefore are labeled as removed. The remaining of the unlabeled features of the target 3D CAD model are also unique features and therefore are labeled as added. The removed and added features of the 3D CAD models are colored red and indicated in Figures 10 (k) and (l). Finally, the differences between the compared models are as shown by the annotations in Figures 10 (m) and (n). The width of a flange is the dimension from side to side, and the length is the dimension from the bottom to edge of the flange.

4   DISCUSSION

The importance of MDI solutions for effective and efficient information reuse workflows has drawn researchers' attention to propose methods to compare 3D models in various ways.

(a) mapped attachment holes / mapped web

(b) mapped attachment holes / mapped web

(c) mapped corner / mapped tooling hole / mapped corner / mapped corner

(d) mapped corner / mapped tooling hole / mapped corner / mapped corner

(e) mapped corner (commonality) / mapped attachment holes (commonality) / mapped web (commonality) / mapped tooling hole (commonality) / mapped corner (commonality) / mapped corner (commonality)

(f) mapped corner (commonality) / mapped attachment holes (commonality) / mapped web (commonality) / mapped tooling hole (commonality) / mapped corner (commonality) / mapped corner (commonality)

(g) mapped attachment flange / mapped attachment holes / mapped tooling hole

(h) mapped attachment flange (differed) / mapped attachment holes (differed) / mapped tooling hole (differed)

(i) mapped stiffening flange

(j) mapped stiffening flange (differed)

(k) joggle (removed) / corner (removed) / deformed flange (removed) / attachment hole (removed)
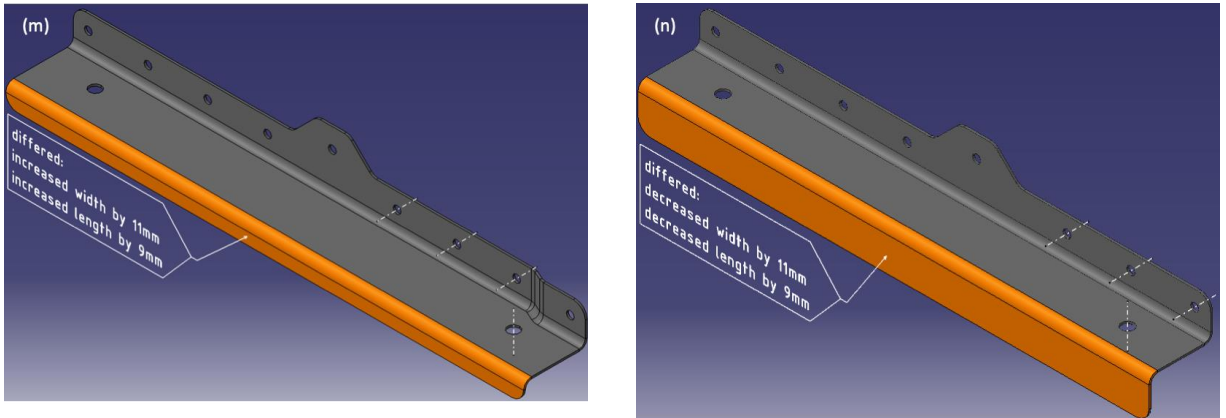
(l) corner (added)

Figure 10: Difference identification of two versions of a 3D CAD model of an ASM part.

The MDI problem have usually been addressed in a primary pose registrations stage and a secondary difference identification stage. None of the previously proposed pose registration methods take design intent, functions or design features into account. Moreover, none of the previously proposed difference identification methods, although feature-based, take design intent or features' functions and purpose into account, rather the major emphasis has been put on feature-graphs comparison. In this work, the significance of design intent and features' functions and purpose in both pose registration and difference identification have been recognized and put to good use in the proposed method. In fact, the underlaying assumptions in this work are that the compared models represent parts with similar-enough functions and that the functions are served by the same features. The steps are based on a set of principles that are explicitly expressed in the following:

1- Any type of parts has a base feature, e.g. the web, that must be involved and prioritized in pose registration;

2- Any type of parts has a number of absolutely essential features, e.g. attachment flanges and attachment holes, that are needed to design any useful and functional part and must be involved in pose registration;

3- Identifying commonalities between compared parts based on mapping features in the features structure of each part and verifying identical parameters between the mapped features must be prioritized to perform difference identification; and

4- Difference identification must be able to differentiate partially different features, e.g. differed features, from added and removed features.

Based on the first two principles the smallest set of features, i.e. the web, attachment flange and attachment hole, was selected to propose the pose registrations method. These principles are applicable to any MDI solution regardless of the domain of application for which the compared parts are designed. One main strength of this work is the simplicity of its premises and principles, which makes them applicable to a wide range of part types.

Here, ASM parts were used to show the proposed method, because their feature structure and feature-function links are industrially established. In some way this is a limitation of the presented work since ASM design use a limited number of features. However, future works could focus on implementing and adjusting the proposed method to compare parts of domains of application with different feature structures like machined parts.

5 CONCLUSION

This work presented an innovative semantic model difference identification method. It compares 3D CAD models represented as feature structures and identifies their differences based on engineering semantics by evaluating the models' features. The proposed method includes two major stages: semantic pose registration and difference identification.

Semantic pose registration provides the opportunity to register the compared models based on their feature structure and their parameters, both of which convey meaningful engineering information and design intent. Semantic registration takes advantage of design intent, and hence of parts' functionality to meaningfully register the models. It also decouples registration from the feature recognition process. Involving parts' functionality in pose registration rather than mere parts' geometry conveys significant value to the proposed method, indicating successful pose registration as the index of comparability of the models. Here, the semantic registration was based on webs, immediate-attachment flanges and the attachment holes on them. The web is the only feature whose purpose as the base feature mandates its existence in all ASM parts.

In order to identify differences, the proposed method relies firstly on eliminating commonalities between the models. Excluding the commonalities of two objects from their comparison results effectively identifies their differences. Thus, we proposed to begin the difference identification process by means of a number of initial steps to identify and exclude the commonality between the feature models (commonality segregation), and to then identify and characterize the differences. Since it is based on the models' features, the model difference identification method proposed here increases the semantic level of the comparison, which would not be possible by comparisons based on simple geometric elements. Both the semantic registration and the difference identification methods proposed here are essentially novel for their integration of the features' design purposes in the comparison process. No similar methods have been proposed. The concept of segregating commonalities in order to group differences has not yet been explored, and this work shows its useful application.

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