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Computer Aided Design and Finite Element Simulation Consistency

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Computer Aided Design (CAD) and Computer Aided Engineering (CAE) are two significantly different disciplines, and hence they require different shape models representations. As a result, models generated by CAD systems are often unsuitable for Finite Element Analysis (FEA) needs. In this paper, a new approach is proposed to reduce the gaps between CAD and CAE software's. It is based on new shape representation called mixed shape representation. The latter simultaneously supports the B-Rep (manifold and non-manifold) and polyhedral representation, and creates a robust link between the CAD model (B-Rep NURBS) and the polyhedral model. Both representations are maintained on the same topology support called the High Level Topology (HLT), which represents a common requirement for simulation model preparation. An innovative approach for the Finite element simulation model preparation based on the mixed representation is presented in this paper, thus a set of necessary tools is associated to the mixed shape representation. They help to reduce the time of model preparation process as much as possible and maintain the consistency between the CAD and simulation models.

Keywords: CAD-CAE consistency, FE simulation model preparation, mixed shape representation, simplification feature, High Level Topology

0 INTRODUCTION

One of the main problems found in the passage from CAD to CAE is the lack of intersecting application space between these two categories of applications [1] to [3]. CAD models are typically generated to create a product shape satisfying functional requirements without prior knowledge of their effects on downstream CAE applications like FE mesh generation. This configuration is originated by the fact that most frequently, simulation software is not integrated with the CAD software environment. Hence, a model exchange is necessary and engineers in this process have different skills: design and engineering if they use CAD and FE simulation otherwise. To generate a FE model, the CAD geometry has to be adapted and often simplified to suit the hypotheses of the needed mechanical model. This task cannot be performed solely on the basis of geometric data, but requires also engineering expertise to supply the necessary additional information, such as Boundary Conditions (BCs). Therefore, a direct automatic transition from a CAD model to a FE model is not feasible [4].

Moreover, considering that due to time pressure and the newly available technologies, the various activities are not carried out sequentially anymore but the so-called concurrent engineering approach is more and more adopted.

The sequential approach is subjected to back and forth cycles between CAD and FEA, thus requiring longer time for product development.

Whereas the concurrent engineering paradigm assumes that when possible, the activities are carried out in parallel to provide results evaluation as early as possible. Therefore, a simulation analysis might be carried out at different design stages, bringing to new consistency issues as described below.

Therefore, at a given stage of the design process (time T0) some preliminary analysis can be executed (see Fig. 1).

At this time, mechanical hypotheses and simulation objectives are inserted to generate a domain of study compatible with the simulation requirements (see Fig. 1).

As a result, the model M, called the case of study, is obtained and enriched with BCs.

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From M, a FE mesh M' is derived to form the basis of structural analysis. T1 reflects the duration of the overall analysis process. Finally, at time (T0 + T1) the analysis results AM are obtained from mesh M' enriched with the proper mechanical parameters. Such workflow illustrates the standard operations required to perform an analysis. The results AM are mandatory to validate this analysis process. As a consequence, a new analysis at T2 can be initiated only after this process has been validated (T2 > (T0+T1)). Now, considering that a modification of the initial CAD model has taken place to fit new product requirements or to derive a new version of the component, this implies that the case of study has to be updated (M'', at T2). Here, the question is raised whether or not mesh M', derived from the model M'', is still acceptable to model the behavior of the structure of M'' or if a new mesh M''' needs to be produced to perform a new analysis. If mesh M' can be derived from M'', then the performed modification on the initial CAD model M has no impact on the analysis results. Otherwise, a new mesh M''' is required to perform a new analysis.

Hence, the consistency between design and simulation views is achieved through models M, M', M'', M''' if their coherence is preserved during the product development process, i.e. M' is attached to M'' for the first simulation objectives or M''' is attached to M'' for the second analysis objectives. Such a configuration of consistency is called a one way consistency between simulation and CAD models.

As depicted through the above configuration, the consistency between CAD and simulation models strongly depends on the adaptation process, i.e. the process which ranges from the generation of the case of study (models M and M'') to the FE mesh (models M' and M''').

In structural analyses, several mechanical models may be necessary to evaluate the behavior of components. These models are based on different meshes corresponding to different datasets according to the analysis objectives, e.g. structural analysis and thermal analysis. Currently, the models involved cannot be maintained coherent because there is no strong model link between the case of study models and FE meshes. Establishing such a link triggers also the consistency between the design and simulation views [5].

This paper attempts:

- To provide flexibility in combining different shapes with the same model representation called High Level Topology (HLT), for FEA model preparation purposes (see section 2.2).
- To develop a new methodology and tools which enables the analyst to selectively choose and extract the desired geometric entities from a several source of input shapes (CAD models, form features models, pre-existing meshes, ...) for the purpose of creating the FEA model (see section 2.3).

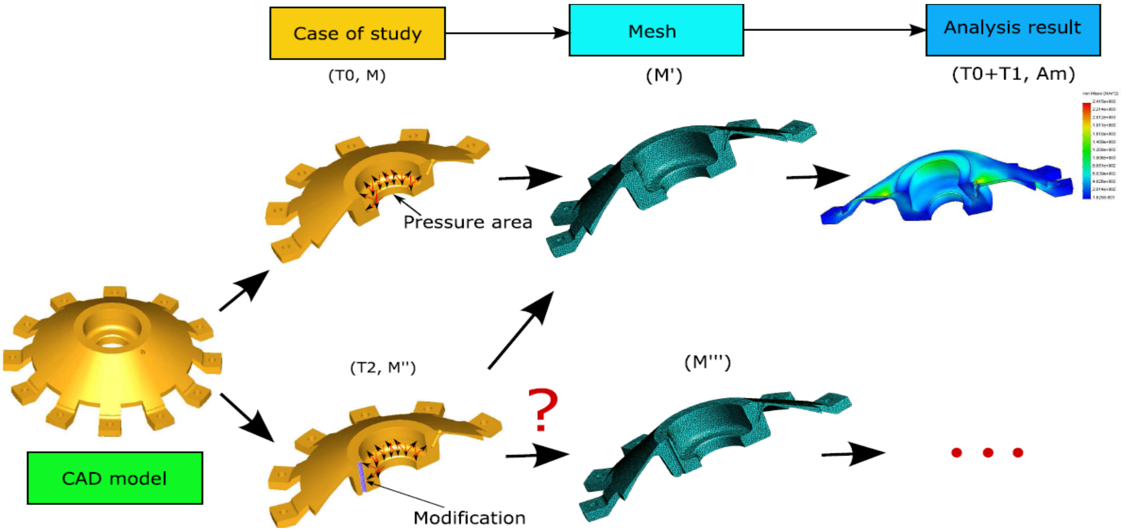


Fig. 1. *A consistency configuration: shape modification of a CAD model*

- To address the above problems and to bridge the gap between CAD and CAE models, but also to maintain consistency between all the input models (see section 2.1).
- To reduce the complexity of FEA model preparation; then the concept of simplification features will be proposed for referring to a relevant concept to reduce the time of the adaptation process (see section 2.3).

1 RELATED WORKS

Among the various research areas covering the CAD-CAE consistency, essentially two address some of the aspects related to product views:

1. The form feature approaches are based mainly on the feature information identified on the B-Rep model or attached to it during its generation. Using this type of information, the resulting object description is composed of a set of form features, which can be simplified directly on the CAD model, according to the simulations objectives. Authors assume that the initial B-Rep model is consistent [6] and [7], which is true when considering an integrated feature-based software environment. One such simple configuration is exemplified with industrial CAD software using a construction tree with feature-like primitives. However, this hypothesis is not valid in the industrial context when the form feature model needs to be transferred from a CAD system to a FEA environment; the graph of the form feature is lost when standard file format is used. In addition, identifying or attaching form features incorporating free-form surfaces and exchanging feature information among different software through standard format is still a strong limitation of these approaches. Form features approaches also suffer from limitations because they rely solely on geometric information, whereas simulation Information is mandatory to characterize details.

2. The polyhedral approach [8] and [9] can be applied to tessellated models, digitized models or even pre-existing FE meshes since a triangulation can always be obtained from these models. Thus, the polyhedral model can be considered as an intermediate model between the CAD model and FE mesh generation. When this type of approach focuses on the direct use of triangulation obtained from the digitizing phase, it avoids the construction of a CAD (NURBS) model from the digitized points and can provide directly either the FE model required for the analysis or the adapted geometry required to generate the FE mesh. This type of approach requires some healing or conformity set up processes [10], prior to the simplification process. These processes are complex and difficult to perform robustly because the variety of defects encountered is not a finite number of patterns and the target topology of the model after healing, i.e. the topology of the initial NURBS CAD model if the input triangulation comes from such a model, is not known explicitly, because no direct link exists between the initial CAD (NURBS) model and its tessellated model.

Obviously, such topology information could be very useful to make the conformity set up process robust and to monitor the shape changes during the simplification process, and also to check the consistency between the initial CAD model and its polyhedral representation. In this approach the link between the CAD (B-Rep NURBS) model and its polyhedral representation is not maintained. Only the geometric information obtained from a face-by-face tessellated B-Rep model is available and the initial topology of the CAD model is not explicitly defined on the resulting polyhedral model.

In our application scenario, we aim at dealing with various types of input data, such as CAD models, scanned objects or pre-existing FE meshes, therefore the polyhedral model seems to be the common representation for the preparation phase of FE models, as opposed to the use of a CAD model [7]. In order to take advantage of all the available information, especially from CAD geometry and form feature models, it is necessary to bring new solutions enabling the management of the various possible input models to increase the efficiency of an analysis model preparation process for structural analysis. As depicted through the previous analysis, the data exchange standard plays an important role in the process of FEA model preparation in terms of model conformity. The above analysis also demonstrates that the extraction of some geometric parameters and other CAD model attributes is critical in obtaining an efficient model transfer for FEA preparation. The objective of the proposed approach is to preserve the advantages of the existing approaches while extending the efficiency of polyhedral models to exploit the richness of CAD models where it can be useful for the model preparation. From the CAE point of view, few works have addressed the problem of maintaining the information between a FE model and the CAD model representing the shape of a simulation model [11] and [12] by mainly using attribute structures.

2 OVERVIEW OF THE PROPOSED APPROACH

2.1 Mixed Shape Representation for CAD-CAE Consistency

For the above stated reasons, an automatic conversion of the CAD model into an analysis one is not possible in general. Most of the time, such a conversion first requires a selection of a sub-domain of the object on which the analysis can provide results comparable with those obtained on the whole object, which is normally designated as the case of study definition. To avoid the editing of complex CAD models and to ease the integration of the preparation process into a wide variety of design configurations and input data, the approach proposed here is based on two simultaneous representations. The first one is the B-Rep NURBS model imported from STEP files, and the second representation is the polyhedral model generated by the proposed tessellation process. The main objective of such a mixed representation is to reduce the gap between the CAD and simulation fields, and to give our approach more robustness by exploiting the advantages of both representations.

Our proposed approach considers the CAD (B-Rep NURBS) as a reference model (or master model) in the CAD environment. This means that the B-Rep NURBS model is the most faithful representation of the component ``as manufactured" (see Fig. 2). In the CAE software environment, this representation becomes a slave of the mixed representation defined by the HLT and polyhedral representations. This change is justified by the fact that all the simplification operators are performed on the polyhedral model, which provides a robust and flexible representation because the faces are exactly adjacent to each other and general shape changes may be performed.

However, this polyhedral representation is not sufficient to address high level operations. Then, it requires a HLT and geometry support to reflect the initial topology of the B-Rep NURBS model and to ensure the efficiency of the detail removal operators. Our idea intends to maintain both representations simultaneously in order to take advantage of each one at each step of the FE model preparation process. For these reasons, it is mandatory to maintain the link between both representations during the FE simulation model preparation in order to evaluate the impact of any modifications performed on the CAD (B-Rep) model on the FE simulation model. Indeed, it is during the FE model preparation process where shape transformations are operated that there is a need to refer simultaneously to both representations in order to be able to propagate information across these models and hence, preserve the “link” across them.

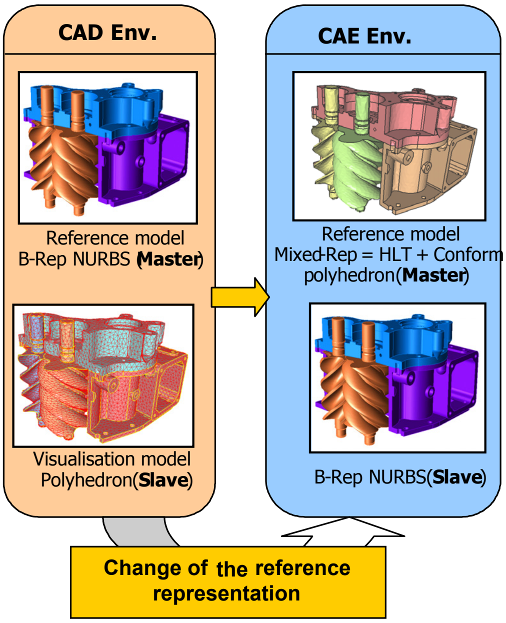


Fig. 2. *Change of reference model during the FE simulation model preparation*

2.2 The High Level Topology

The concept of High Level Topology (HLT) aims at efficiently supporting all the processes and the models involved in the FE simulation model preparation. The HLT concept can be applied to handle either manifold and non-manifold objects. Therefore, it can be used to represent all the required shapes, i.e. the product shape (described as a B-Rep or a feature-based model), the simplified one for the simulation purposes (described as a polyhedron, possibly with idealized areas), and the shape of the BCs as well as other key concepts for the FE preparation process. The overall structure of the HLT data structures and NURBS geometry is also described to highlight their relations.

The new topological representation should satisfy the following requirements [13]:

- to support non-manifold representations for the adaptation and the idealization processes,
- to describe the object's topology at the level required by the user to provide him (resp. her) the concepts needed to apply some FE preparation operators,
- to support representations of mechanical attributes (BCs, materials ...) providing an explicit description that is intrinsic to the corresponding concepts,
- to contribute to the polyhedron conformity set up process,
- to describe the geometry and topology required to specify the FE meshing constraints,
- to be able to describe the topology and geometry of the initial component, in case of an input model coming from CAD systems,
- to be independent of any geometric modeler and to be able to be linked to any CAD/CAE software without modifying the existing tools for shape representations.

The Non-manifold models are constructed using the same basic topological elements of traditional B-Rep, i.e. faces, edges and vertices whereas the connection elements expressing the adjacencies among them have their data structures modified to deal with more generalized configurations. An example of a non-manifold B-Rep is given in [14], where the entity-use has been added to indicate the occurrence of the entity into a higher dimensional element. Thus, a "face-use" element denotes the appearance of a face in an object. Similarly, the "edge-use" denotes the appearance of an edge in a loop of edges around a face. Therefore, an edge may have any number of "edge-uses".

Fig. 3 summarizes these main constitutive elements of the mixed representation. The purpose here is not to describe in detail the corresponding data structures needed to achieve an explicit topological description of the information attached to a shape because of lack of place [15]. Directly linking the topological entities of a polyhedral model to HLT entities is not possible because there is no match generally. To achieve the desired link, 'polyedges' and 'partitions' have been introduced. Polyedges are defined as a set of connected edges of a polyhedron in such a way that it forms a manifold of dimension 1, i.e. the geometric description of a polyedge is a polygon discretizing a curve. Similarly, partitions are defined as a set of connected faces of a polyhedron so that it forms a manifold of dimension 2, i.e. the geometric description of a partition is a polyhedron, either closed or open, discretizing a surface. Fig. 4b illustrates these concepts on a simple component. This structure is one of the main advantages of the mixed representation to propagate and transform the shape and the 'semantic' information attached to it, as depicted in Fig. 5.

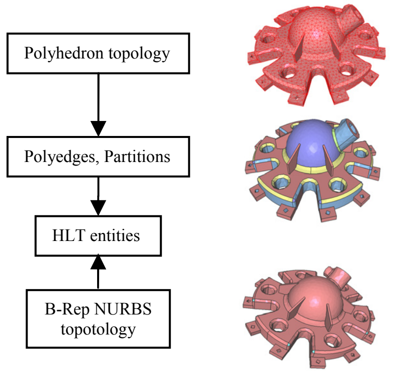


Fig. 3. *Main constitutive elements of the mixed representation and corresponding relations (courtesy EADS CRC)*

As illustrated below, with the operators acting on this data structure, the links between all these topological entities are dynamically updated during the shape transformation processes.

The concept of mixed representation shows that B-Rep NURBS models input must be converted to a facetted representation. At the level of the tessellation process, both types of models must have the same topological invariants, i.e. Euler characteristic. Details about this phase can be found in [16]. The key feature of this tessellation operation is its ability to preserve the largest possible amount of information available in a B-Rep NURBS model, considering that shape exchanges among product views is an important aspect of the product development process where different software is used. Based on tests with industrial major industrial software, i.e. CATIA from Dassault Systèmes, Pro/E from PTC, IDEAS from SDRC, etc., STEP standard appeared the most robust and efficient standard for the transfer of shapes. As highlighted in previous works [16], this standard enables transferring the topology of a B-Rep NURBS model. Its geometry is based on NURBS curves and patches and geometric parameters of analytic surfaces for the NURBS patches describing this category of surfaces. This property contributes actively to the propagation of key information about shapes throughout the product development process.

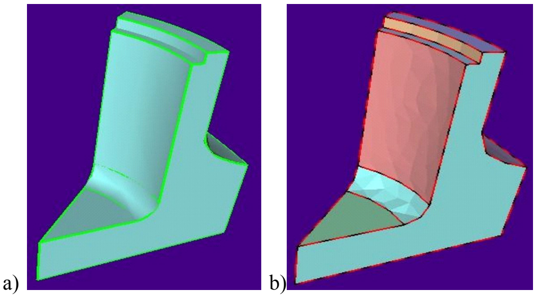


Fig. 4. *Illustration of polyedges, partitions, B-Rep NURBS edges and faces attached to HLT entities; a) B-Rep NURBS representation of the component with edge in green and faces in light blue, b) polyhedral representation of the component with polyedges (dotted red/black polylines) and partitions (a different color per partition)*

As a complementary point, STEP standard incorporates another important feature from the robustness point of view when exchanging shapes between CAD and other software used in downstream product views. Since STEP standard describes trimmed NURBS patches with the 3D intersection curves between adjacent patches in addition to the corresponding trimming curves in the parametric space of each patch, this 3D description can be used to robustly generate a conform polyhedron. Indeed, these curves can be discretized and then effectively serve as common boundary between the polyhedrons describing the NURBS patches. Processing patches that way is, in fact, modeller tolerance free because this discretization scheme does not take any modeller tolerance into account as it is necessary during intersection computations or other geometry processing taking place during NURBS model generation.

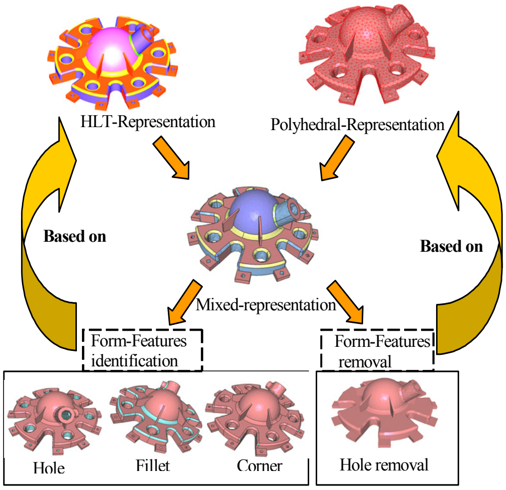


Fig. 5. *Advantages of the mixed representation: HLT data structure plus NURBS and polyhedron representations*

The concept of HLT has been introduced here to meet the requirements identified in the previous sections for explicitly representing the semantic information attached to a shape. In addition, the objective of the HLT is also to enable the intrinsic representation of some semantic information attached to a shape. To illustrate these two complementary concepts, the following example can be considered.

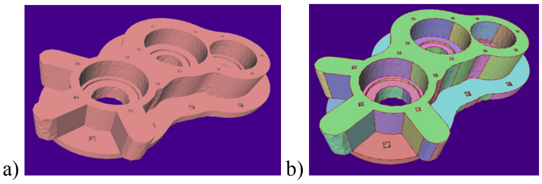


Fig. 6. *Illustration of HLT entities on a component; a) initial component represented as a polyhedron, b) polyedges, partitions reflecting the B-Rep NURBS decomposition produced by a CAD modeller*

Fig. 6 depicts a component after the generation of its facetted representation from the

STEP file input. Using this file content, the topology of this component can be inserted in the HLT data structures. The concept attached to this decomposition is that it reflects the trace of the component modelling process in the industrial CAD software used to generate it. This decomposition may have an interest if interactions are needed between the 'current PV' where the HLT is used and the product view where the CAD modeller has been used.

Fig. 7 describes another HLT decomposition of the component where the concept represented is the geometric shape features attached to the component. Here, partitions are associated to a surface type meaning, i.e. planes, cylinders, cones, etc. based on the information available in the STEP file input. This HLT instance is the intrinsic representation of the shape features belonging to the component surface and it is an explicit topological representation of the component surface according to this feature concept. This HLT instance, like the HLT instance in Fig. 5 both rely on vehicular in information only.

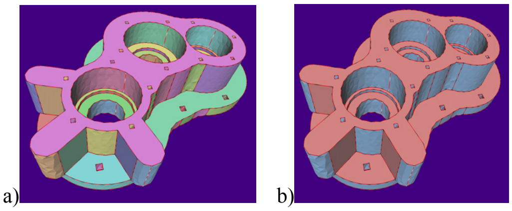


Fig. 7. *Illustration of a HLT instance representing shape features; a) partitions decomposing the component according to shape features, b) the same partitions coloured according to the surface type (pink for planar areas, blue gray for cylindrical areas)*

Fig. 8 represents an HLT instance of the component surface decomposition into sub domains as they are needed for a FE mesh generation process. Dotted white/red polyedges indicate that they are no longer the effective boundary of HLT partitions. Here, it has been considered that the sub domains generation could take into account the shape of the object as well as the size of the FE desired and the local minimization of the discretization error. As a result, this decomposition results both from vehicular in information and vernacular one specific to a product view focusing on FE simulation model preparation. Such a HLT instance can be generated either on a semi-automatic basis if the actor's know-how cannot be formalized enough or automatically if the criteria needed are entirely formalized. Here, the concept explicitly and intrinsically represented is the component decomposition according to FE mesh discretization constraints.

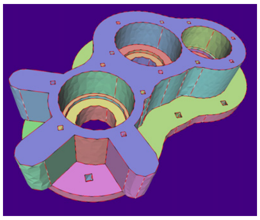


Fig. 8. *Illustration of a HLT instance representing sub domains for FE mesh generation; the component surface decomposition reflects the sub domains needed for the domain decomposition into FE*

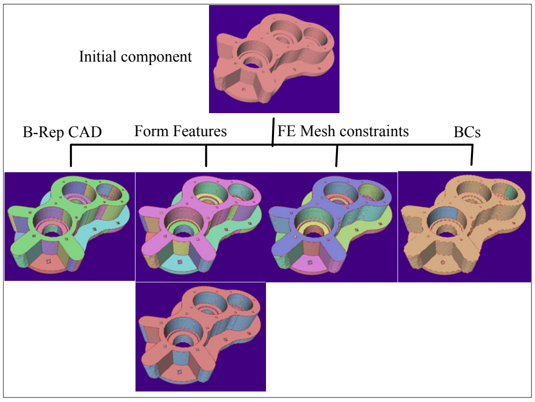


Fig. 9. *Synthesis of HLT instances attached to a single component and describing explicitly the topology of semantic information represented intrinsically*

Fig. 9 gives another example of HLT instance describing Boundary Conditions (BCs) applied to the component for a given FE simulation. According to the corresponding semantic, partitions could be further subdivided to describe more precise concepts, e. g. pressure areas and clamped areas. Again, the corresponding component decomposition is an explicit topological description intrinsically dedicated to the concept of BCs. In line with the HLT instance described in Fig. 9, this HLT instance also relies both on vehicular in information and vernacular one.

The example described above has illustrated the concept of HLT instances attached to a component. It should be pointed out that each of these instances can be of type non-manifold to preserve the intrinsic representation of the corresponding concepts. This further generalizes the contribution of Bronsvoort [17] and [18] focuses on cellular type decomposition of objects. A further point considering the HLT instances is that they can be all attached to the same component instance. This can be graphically synthesized with Fig. 8 where the boundary partitioning reflecting the concepts in Figs. 6 to 9 are all attached to the initial component [19].

2.3 Process Flow of the Proposed Approach for CAD-FE Simulation Consistency

Fig. 10 illustrates the structure of the proposed FE model preparation process, starting from a CAD model (possibly feature-based) enriched with additional mechanical information (A) and finishing with standard FE mesh generators and solvers (C). This structure clearly shows that the preparation process can be inserted in any CAD-CAE software environment without modifying the existing tools. Standard CAD modelers are distinguished from feature-based ones to clearly cover all the possible industrial configurations, i.e. CAD modelers that can use a variable range of form feature primitives. In this paper, we restricted to B-Rep models since they are always available through standard data exchange formats, e.g. STEP. The preparation process (B) can be applied to different input polyhedrons, i.e. evaluated from CAD models, digitized models or pre-existing FE meshes. Even if this capability is not under focus here, it is shown to reveal the overall model preparation scheme to demonstrate how this scheme behaves depending on the amount of information existing in the input model. The architecture of the proposed approach is composed of three blocks.

1) Block (A) Represents the Level of Geometric Modelers

At this level (see Fig. 10), standard solid modelers can be associated with a process, namely the insertion of BCs, to produce the case of study. The case of study designates the component sub domain that is required for the targeted FE analysis in accordance with the mechanical hypotheses as well as the location of prescribed forces and/or displacements defining the loading conditions over the component. However, this process is not mandatory and, if not performed at that stage or if not entirely performed at that stage, should be possible later in the FE model preparation process.

The generation of a case of study is often based on some of the BCs required to set up or to simplify the analysis model. Symmetry planes, pressure areas, force locations are the most recurrent BCs.

Most of them are inserted through the use (and possibly creation) of adequate geometric elements; thus motivating at CAD level some of the BCs insertion process that should be specified and then transferred to the HLT and polyhedral representation.

Geometric operators of standard CAD modelers as well as specific ones are used to create the geometric model of the case of study, which is often non-manifold. Whilst the geometric model can be exported at model preparation level through a standard format such as STEP, BCs parameters that coincide with the mechanical parameters attached to the geometric model of BCs, i.e. pressure values, forces components, are not incorporated in the STEP application protocols used by most of CAD systems, i.e. AP 203 and AP 214. Thus, BC parameters currently need to be transferred through specific file formats to input them into the model preparation environment if they are defined outside this environment.

Feature based modelers are distinct from standard solid modelers because there are still limitations in handling feature information in standard formats. Similarly, not all these modelers treat the same set of feature primitives. As a consequence, three categories of data are returned from these modelers:

1. A geometric model of the component that can be exchanged through a STEP file. B-Rep models in STEP files (AP 203) are defined as “a geometric representation through several layers of topological representation items, reference curves, surfaces, and points” and incorporate various levels of geometrical and topological information [20];

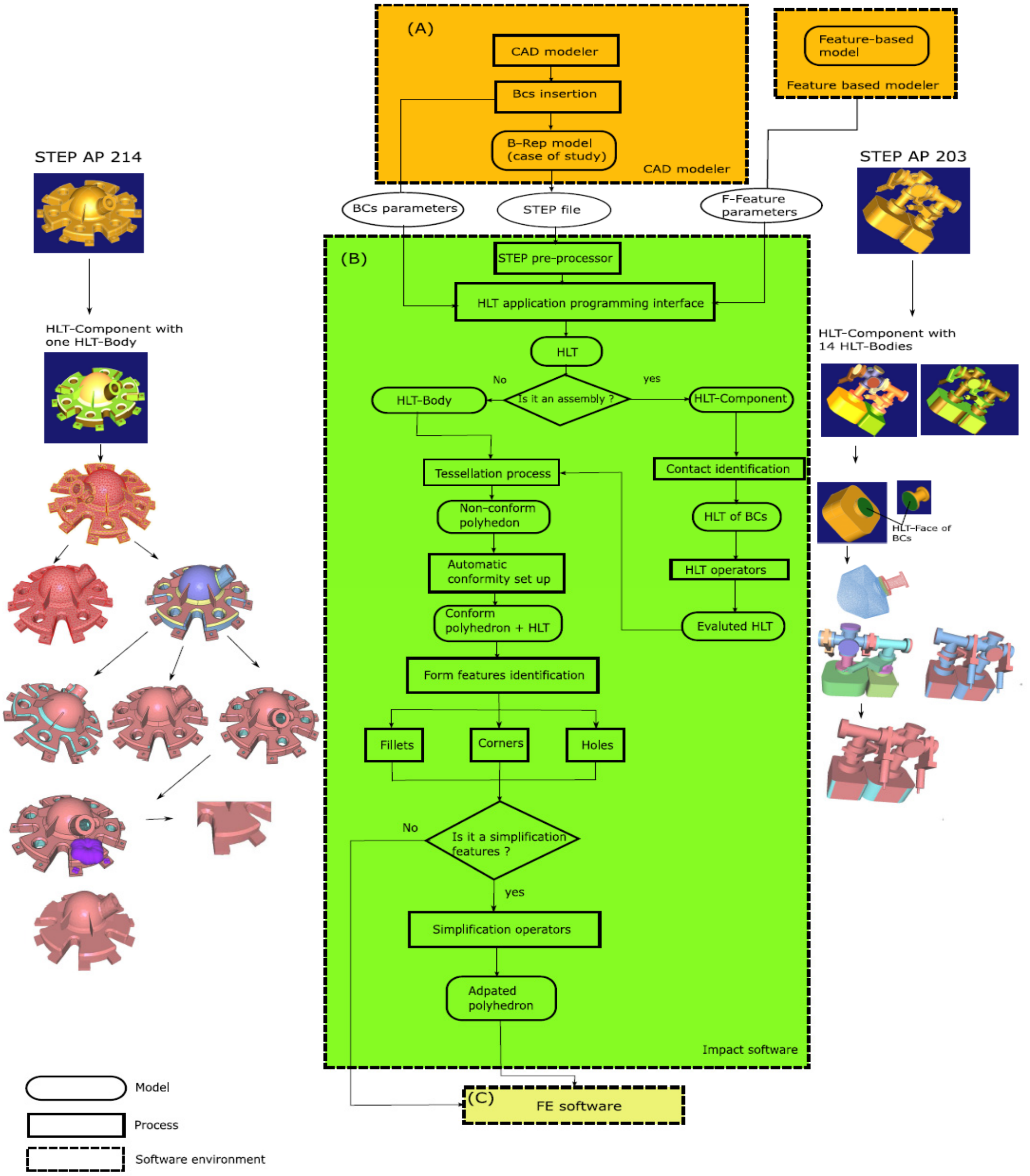


Fig. 10. *Process flow of the proposed approach*

2. A set of feature parameters and data to describe the form features present in the component. This requires a specific file format since STEP files cannot incorporate such a type of information yet;

3. A set of BC parameters to describe the possibly defined mechanical parameters.

It should be noticed that the geometric semantic attached to some primitive curves or surfaces, i.e. the nature of circles, line segments, cylinders, etc., can be further exploited during the preparation phase to enrich the polyhedral description with the primitive parameters and to help the extraction of the simplification features as stated later at section 2.3.4.

In addition, the AP 203 contains other type of information, like the assembly information, which is not supported by AP 214. This information is useful for the proposed approach to specify the BCs on a component during the shape transformations taking place in the FE model preparation.

The contact area between components of the same assembly can be seen as the geometric domain where BCs can be applied.

This type of information is neither explicitly available in STEP or in a CAD software environment. Only the spatial relationships between the components of an assembly are stored as a graph, which reduces them to logical links only.

In our context, the exploitation of such a kind of information represents the first step for the geometric domain identification of BCs. This type of information should be maintained on the HLT and transferred to the polyhedral model in order to define the geometric domain of BCs.

Indeed, these contact area identification needs to be performed on the initial B-Rep NURBS representation of the assembly either as a specific function inside a CAD modeler, i.e. the block currently described, or as a function in block (B) (see Fig. 10).

Since the data exchange standard plays an important role in the process of FEA model preparation in terms of model conformity, the above analysis demonstrates that the extraction of some geometric parameters and other CAD model attributes are critical to obtain an efficient model transfer for FEA preparation. The objective of the proposed approach is to exploit simultaneously the advantages of both representations, i.e. B-Rep NURBS (through the HLT model) and polyhedral models, in order to reduce the tedious work of the adaptation process as much as possible. The first representation is the HLT one with the NURBS model, contributes to identify the form features which can be details, and is used to perform the conformity set up automatically.

The second representation is the polyhedral one and contributes to perform robustly the detail removals. Both representations are mandatory for the robustness of our approach.

2) Block (B) Represents the Processes Related to the FE simulation model generation in accordance to the FE model preparation requirements

A common requirement is the capability of explicitly representing the topology related to BCs, material which led us to propose a concept of HLT discussed in the previous section. In this section we describe the processes related to the use of the HLT. These ones can be applied either on a HLT-Body (left set of images in Fig. 10) or on a given HLT-Component (right set of images in Fig. 10) with several HLT-Bodies, i.e. an assembly.

Such configurations can be distinguished according to the used STEP protocol. The resulting model from a STEP AP 214 pre-processor can only be a HLT-Component with several HLT-Bodies without logical links between them, whereas the resulting model from an AP 203 pre-processor can be either a HLT-Component with a set of disconnected HLT-Bodies and logical links between them or a set of HLT-Components with logical links between them, each of them containing only one HLT-Body.

In order to perform efficient shape simplifications during the FE simulation model preparation, four steps are proposed before the preparation process itself:

2.3.1 Model Conversion from STEP to HLT and Polyhedral Representations

To reflect the topology and geometry of the initial object to be analyzed, the HLT is created directly from the object B-Rep NURBS. Firstly, the STEP entities are loaded into the B-Rep CAD data structure of a hosting CAD modeler [15]. In the implementation described in this paper, we used Open Cascade as the geometric modeling hosting system. At this level, non-manifold solid models were considered as they can be available in CAD systems through STEP files. Even though all of the major modeling kernels are B-Rep based, they all have some differences in how they represent that topology.

The topological entities are mapped between the STEP file and HLT data structure. In the first place the STEP entities are loaded into classical B-Rep CAD data structures. Here, these data structures are that of the geometric modeling kernel available from Open Cascade. At this level, non-manifold solid models have been considered, as available in CAD systems. Even though all of the major modeling kernels provide a boundary representation of the model, they all have differences in how they represent that topology. To expose all of these differences to the rest of the geometry-based environment would greatly complicate the software architecture. By providing a consistent interface, the FEA model preparation data structures are isolated from these differences, which are all encapsulated in the model interface classes, i.e. the shape kernel interface.

2.3.2 Tessellation Process

A tessellation process to convert the HLT of B-Rep NURBS model into a polyhedral one whose discretization must be compatible with a given FE map of sizes defined *a priori*.

The model preparation environment for the above range of data starts with the tessellation of CAD data to produce the polyhedral representation required for the detail removal process [5].

Rather than using a tessellation process integrated into CAD modelers, where the criteria used can vary widely from one modeler to another and the control parameters may not be suited to the FE simulation preparation process, i.e. the lack of control parameters may produce very sharp triangles that are not compatible with the range and accuracy of the simplification operators applied later on, a specific tessellation process has been developed.

This process is independent of any CAD software, it uses Ruppert's algorithm [21], and adopts an edge length criterion while avoiding degenerated triangles.

Incorporating the tessellation process into the model preparation phase offers also the possibility to relate its control parameters to the detail identification taking place later on. However, it should be mentioned that there is not yet any clear specification of operators to bind efficiently the tessellation to the simplification processes.

Thus, the tessellation process by itself needs to be controlled by the mechanical engineer in charge of the simulation to ensure that the discretization of the CAD model is somehow compatible with the FE size required in the FE mesh.

The polyhedral model generation forms the basic step in the overall adaptation procedure because the operators efficiency of the adaptation process strongly depend on tessellator characteristics, i.e. density of elements, conformity of the polyhedron generated by the tessellation algorithm.

The faces of the output polyhedron are constrained by form (no very small angles to avoid numerical instabilities) and size (edge length lower than a given size) requirements in order to produce a satisfactory shape adaptation.

2.3.3 The conformity Set Up Process

To produce a conform polyhedron as needed by the simplification process, a conformity set up process is mandatory for the tessellated CAD models as well as for the digitized ones. Even pre-existing FE triangulations may require such a treatment when the objective is to set up a model from several parts to merge them into only one HLT-Body.

In the case of CAD model input, generating a conform model means that the topology of the polyhedral model must be identical to that of the initial B-Rep NURBS model as it is available in the STEP file. In other words, for a two-manifold closed surface representing the boundary of a volume, each edge of the corresponding polyhedron must be connected to exactly two faces and the genus of the polyhedral model must be identical to that of the volume in the STEP file. The configuration of non-manifold models is not specifically addressed here since STEP does not incorporate capabilities to describe the topology of such objects. In addition, as previously discussed, industrial modelers are not offering specific and efficient operators to generate such models. In the [22] the authors present a connection between the mesh and the parametric generation with a CAD kernel for a selected structure generation. Such configurations only occur for simple shapes handled in a so-called integrated environment. However, it is no longer efficient when the CAD model has an inconsistent topology due to data exchange between different software or to the difference of shape requirements between FE meshes and CAD models. Indeed, certain topological details may severely complicate the mesh generation, and the quality of the resulting mesh is not always suited to the simulation objectives.

In general, the conformity set up process based solely on the polyhedral model input cannot be performed robustly because it requires a specific set of tolerances related to the model source [13].

In order to robustly achieve the conformity set up process, the topological information available in the HLT data structure can be used to apply some conformity set up operators on the tessellated model and achieves its conformity.

To this end, the following classification of the HLT entities helps defining the process principle (see Fig. 11).

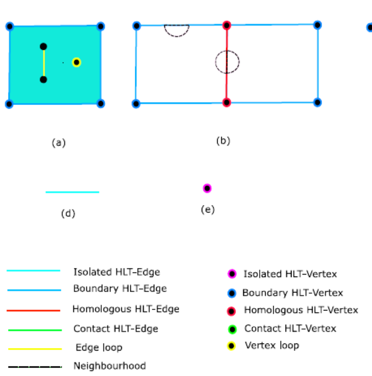


Fig. 11. *Illustration of HLT entities classifications*

A HLT-Edge which does not take part to the description of any HLT-Face is classified as an isolated HLT-Edge (see Fig. 11d).

From the above list of edge status (see Fig. 10), the concept of homologous edges is the key status required to characterize the polyhedron conformity needs between polyedges. Therefore, it is the only status that needs to be implemented for the conformity set up operators.

Again, the vertex classification shows that the status of homologous vertex is the key status for the operators performing the conformity set up process. There, it is the only status that needs to be considered as a basis for the basic operators to be implemented.

As a result of the above analysis, the automatic conformity set up consists in the following steps:

- Merge the list of homologous vertices: first of all, the homologous vertices belonging to the homologous polyedges are collected (see Fig. 12b) and then merged two by two. The results are updated in the list of homologous polyedges (see Fig. 12c),
- Merge the list of vertices associated to the boundary of HLT-Faces belonging to the corresponding homologous polyedges: this step consists in merging the polyedges two by two according to their orientation, which has the same orientation as their HLT-CoEdges. Finally, only one polyedge results from two adjacent boundary partitions. This polyedge represents the discretization of the initial HLT-Edge and has a topology identical to the corresponding edge defined in the STEP file (see Fig. 11d).

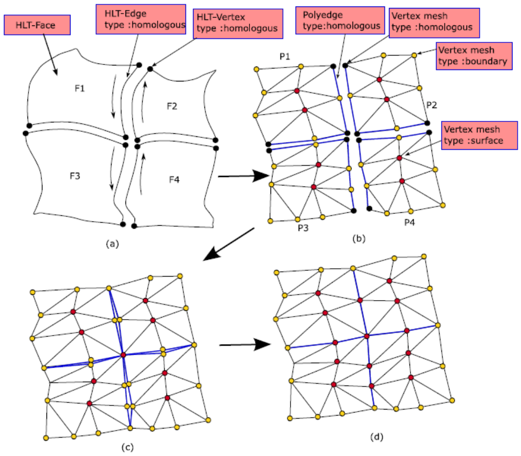
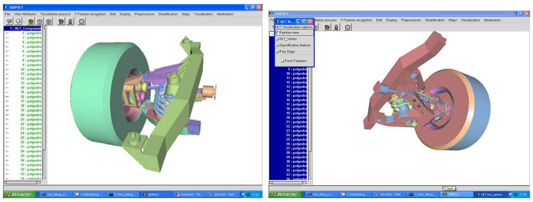


Fig. 12. *Automatic conformity set up process; a) a set of geometrically disconnected HLT-Faces as produced by the STEP pre-processor, but topologically connected at the homologous vertices and along homologous edges, b) corresponding polyhedral model produced by the tessellation process, c) merging of the homologous vertices belonging the polyedges, d) merging of the boundary vertices belonging the polyedges*

The resulting polyhedron is conform, and its topology is identical to the topology of the object initially described in the input STEP file. In conclusion, the conformity set up can be performed automatically and robustly since it is based on topological information provided by the link between the initial B-Rep topology and the polyhedron.

As a result of this approach, the conform polyhedron is bound to the B-Rep topology of the CAD model and if available (see Fig. 13), to the form features.



a) *b)*

Fig. 13. *Example of automatic conformity set up process performed on the imported models in STEP files; a) HLT-Component representing an assembly (each color represents a type of HLT-body), b) HLT description of the initial component and its geometric semantic (each color represents a type of HLT-Face geometry, i.e. plane)*

2.3.4 Form Features Identification

In the previous section, the link between B-Rep NURBS CAD models and polyhedral models was successfully set up through the mixed representation, i.e. HLT data structures, plus NURBS and polyhedron representation.

This new representation, i.e. mixed representation, allows algorithms to exploit simultaneously the advantages of the B-Rep NURBS and polyhedral representations (see Fig. 5) as follows:

- The first representation, which is the HLT data structure plus NURBS geometry, allows algorithms to identify certain form features (holes, fillets, corners), which can be considered as detail features.

New concepts are required to classify these identified form features as feature details. Such concepts lead to the notion of "simplification features" whose objectives are [13]:

- Reducing the complexity of the detail identification and strengthening the tasks related to simplification by enabling reasoning directly on a set of geometric elements belonging to a specific form feature instead of the low level elements only, i.e. vertices, edges, faces of a polyhedral model [23].

Form feature information brings high level information either to complement or supersede polyhedral model data structures,

- Avoiding inconsistencies of information between the CAD models and the corresponding simplified polyhedrons, in such a way that form features which are not relevant for structural analysis do not appear in the simplified models.

This observation is highly significant because an adequate preservation of information during the simplification process contributes to an evaluation of the impact of CAD geometry changes on simulation models, because if the added form features to the CAD model is a simplification feature, then the initial FEA model does not require a re-evaluation.

The second representation, which is polyhedral, allows algorithms to remove certain from features on this model, whose removals solely performed with the HLT data structures and NURBS model can be fairly complex and hence not robust.

Some works have been already performed on this subject [24] and [25], which consists in identifying and removing certain form features on the B-Rep NURBS model.

The majority of these algorithms modify the geometry and the topology of the initial model.

Consequently, these modifications in many cases involve the computation of intersections between 3D curves or surfaces in order to ensure the consistency of the resulting B-Rep model. However, the computation of intersections between 3D curves is not exact and often requires some approximations.

Therefore, these approaches cannot be robust since they incorporate tolerances that generate model consistency problems later on in the downstream processing of the simplified model. On the other hand, this problem does not arise on the polyhedron because of the very simple geometric support of each face, which is exactly adjacent to others through a common edge which is a line segment.

Additionally, most of the approaches addressing the feature removal aspect are based on geometric criteria only, whereas the concept of simplification detail strongly depends on the analysis to be performed, i.e. it relies both on geometric and mechanical criteria. In order to give more robustness to our approach, the form features will be identified on the HLT-NURBS model and then removed on the polyhedral model to create a progressive shape transformation and produce a model that can be robustly transferred to downstream processes.

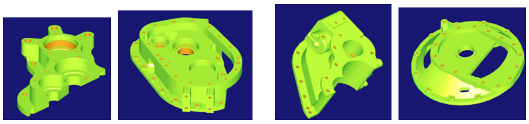


Fig. 14. *Examples of hole identification results using the B-Rep-NURBS/analytic surfaces representation*

The interest of the mixed representation is also to take advantage of the B-Rep NURBS/analytic surface representation to identify some shape feature characteristics. Fig. 14 illustrates the configuration of a hole identification process performed with this representation. Then, based on the partition entities, the description of these holes can be propagated on the associated polyhedron representation. Similarly, fillet features can be identified using the B-Rep NURBS/analytic surfaces description. This is currently applied to simple fillet configurations where basis surfaces are among the analytic surfaces, i.e. planes, cylinders and spheres. Fig. 15 gives some examples of the corresponding results displayed on the polyhedral model.

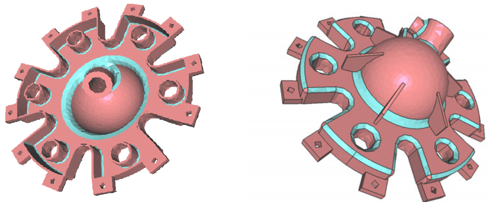


Fig. 15. *Examples of fillet identification results using the B-Rep-NURBS/analytic surfaces representation (courtesy EADS CCR)*

The combination of distance criteria and shape features identified through B-Rep NURBS / analytic surfaces information can provide new concepts for performing shape transformations. The concept of the simplification feature is one of those new concepts and is defined as follows: A form feature F is a simplification feature if F is fully contained in the discrete envelope defined by the map of sizes associated to it. An example of such a feature is given in Fig. 16. It combines the through hole feature identification with local user-defined map of sizes defining the allowed distance between the initial and polyhedrons.

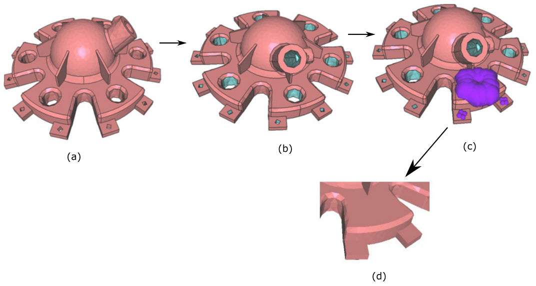


Fig. 16. *Topological detail feature; a) initial component, b) through holes identification, c) local map of sizes defined by the user that contains some through holes, d) result of the simplification operator associated to the simplification feature thus defined*

3 CONCLUSION

This paper proposes a method, models and tools for CAD-CAE consistency. The method consists in setting up a new approach for CAD-CAE consistency based on the concept of mixed representation (High Level Topology data structures, NURBS and polyhedral representations), which allows the software architecture to explicitly maintain the links between these models, to manipulate them and to take advantage of their richness. Exploiting the advantages provided by the information content and organization of each representation, the proposed approach improves the robustness of the various processes involved in FEA model preparation from CAD data and makes the overall conversion more efficient. The concept of HLT is presented in this paper to extend the shape description capabilities of current CAD modelers to satisfy the requirements of simulation models. The defined HLT representation can handle configurations either manifold and non-manifold, which frequently appear in the specification of the underlying geometric support of BCs, in FEA models having idealized subparts and which are useful for the specification of the composing material. Through the use of multiple HLTs in the proposed method, the intrinsic shapes of all the above concepts (BCs, material, object) are explicitly represented and suitably combined through what is called evaluated topology. Transforming B-Rep NURBS to polyhedral representation is one of the processes required for FE simulation model preparation in the proposed approach. Such a process called tessellation is taking advantage of the HLT concept and allows maintaining the link between the B-Rep NURBS information and its polyhedral approximation. During the tessellation the geometric semantic attached to the HLT data structure of a B-Rep NURBS model is used and is propagated onto the polyhedron model. This semantic serves to make the conformity set up process robust. To speed up the shape adaptation step, the concept of simplification features has been proposed.

Such a concept combines the geometric and mechanical data to reduce the complexity of the task of the FE simulation model preparation, and contributes to evaluating the consistency between the various versions of the CAD model of the same object and the already computed FEA models. The geometric data are characterized by specific form features, such as holes and fillets. The mechanical data are characterized by the map of FE sizes defined a priori or posteriori on the polyhedron model. New categories of details features can be derived from the simplification features concept. Topological detail features, and skin detail features are two new categories which can be useful for FE simulation model preparation and that have been proposed. Through hole, fillet and round features are identified on the object model, taking advantage of the HLT data structures and of the attached geometric surface description.

The proposed approach can be implemented into any existing industrial software, without modifying a current preparation process flow if not desired by the users.

4 ACKNOWLEDGEMENTS

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