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A REFLECTION ABOUT REVERSE ENGINEERING FOR DMU MATURITY MANAGEMENT

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1. Introduction

In actual industrial world of full-digital data, 3D representation becomes predominant. In a product design process, the **D**igital **M**ock-**U**p (DMU) has a leading role. A product DMU is not only a geometrical view of a product assembly. It is composed of several views, generally linked to the different expert domains involved in the product definition. Thus, DMU gathers topological and geometrical information, parameters and knowledge such as manufacturing processes of the composing parts, assembly requirements or functional specifications.

The DMU is often motivated by the need of an up-to-date representation of the product along the different phases of its life (as designed – as manufactured – as maintained – etc.). However, in the case of long-time running mechanical systems, DMU is hardly consistent when addressing maintenance or modification product phases: changes on the in-use product are not always reported to the original DMU which becomes rapidly obsolete and does not reflect the reality anymore. In this context, we focus on the representation of these changes in order to update DMU for a more efficient lifecycle management. We therefore focus on the differences between the real model and the virtual one, which are named "maturity defaults". A maturity default can be a component at a different place, a replaced component with a different geometry or the absence of a component. The challenge of identifying the maturity defaults is to determine how to compare a DMU with the real product. Going further in the reflexion, it consists in finding at least, one comparison criteria.

Designers often need to retrieve existing product data for reuse in a CAD environment. In other words, they need to retrieve an "as-built" product model. One general way to get data from an existing component is to digitize it with technics such as laser scanning for example. The result usually consists in one or several point clouds representing the overall shape of the product. Then different methods are used to build a 3D model based on the point clouds. That process is known as **R**everse **E**ngineering (RE). RE can be motivated by several reasons relative to different field of applications. We can cite the competitors' products analysis, the redesign of existing products or the remanufacture a product without information on the original manufacturing processes. These reasons specifically concern long-time working products. In the industries based on concept products, as in the automotive for example, the prototypes need to be digitized to be integrated in the whole product DMU. As an example, within a car frame, the shape is defined by a wood prototype or some concept arts. Abroad from design and redesign contexts, the patrimony conservation is also an application field for RE works, for both industrial and cultural objects [Laroche 2008].

DMU maturity management is close to RE field of research. Within the RE Field, the shape can be used as a comparison criteria. The DMU from a CAD software is then represented by its envelop. The matching between this envelop and the point cloud can therefore be generated using meshing functionalities. On the opposite, further technics consist in shape description that allows the comparison of 3D models through their shapes. The Reeb graph is one of the most popular for the last decade.

This paper proposes to address the second matching technic, based on the use of graphical representation of the DMU and RE representations. This representation is then used within a DMU maturity management process. The graphical representation of the DMU is tested on a basic use case composed of three connecting rods. This paper is structured as follow. First, we briefly present the State of the Art concerning RE methodologies. Existing methods for graphical representation are presented and a strong focus on the Reeb Graph is proposed. Second, observations regarding the use of Reeb graph representations of products for DMU / RE comparison are detailed. Based on these observations, a DMU maturity management process is proposed and future development are described.

2. State of the art

This paper field of interest concerns two domains of research: the RE domain and the shape descriptors domain.

2.1 The reverse engineering

The RE domain of research has been addressed for years. It began with industrial needs 25 years ago. RE methods were first built based on geometrical approaches. We can distinguish two of them, the most important in the literature, corresponding to the two basic ways to represent solid models: the boundary representation (B-rep) and the representation based on features.

First, some studies are about retrieving surfaces and/or primitives in a point cloud [Várady 1997]. The basic process is simple. For the beginning, the model to rebuild is scanned in order to get a point cloud. Then, the point cloud is treated: sampling, noise filtering, etc. The third step consists in the segmentation of the cloud into sub-clouds, B-rep surfaces are then fitted on each sub-cloud. Finally, the surfaces are sewed and the CAD model is created. But fitting surfaces on point clouds is more appropriate for artistic models. The resulting model is generally frozen and cannot be changed (impossibility for changing parameter values, dimensions, etc.). The redesign activity is therefore tedious, if not impossible.

The second kind of works on RE is based on the reconstruction of a model by retrieving geometrical features in the point cloud. [Thompson 1999] is one of the first significant works to use the methodology known as feature based method. In the REFAB (**R**everse **E**ngineering-**F**e**A**ture-**B**ased) project works, using an interactive system, the purpose is to recognize automatically manufacturing features for process planning. The features, corresponding to different manufacturing operations, are selected in a list and the user defines where they are located in the point cloud. Some links between features can be expressed as parallelism or concentricity, for example. The manufacturing feature parameters allow some redesign activities.

More recently, a new kind of approach is proposed: combining geometrical elements with design intents and, at a wider scale, knowledge associated to the considered part. Thus, [Durupt 2008] proposes a **K**nowledge **B**ased **R**everse **E**ngineering interactive method for RE. The authors assume that an expert analysis of the considered part allow the extraction of driving design parameters. In the method, every geometrical features of a part can be justified by a functional specification or by a manufacturing process. It's a two-step method. First, geometrical features, describing functional surfaces or manufacturing consequences, are identified in a 3D point cloud. Then, using a segmentation technic, the parameters of the geometrical features are valued by the recognized geometry in the cloud. A skin is finally generated on the features. This approach proposes to construct an "as-built" 3D model that is close to a CAD model classically generated by CAD software: features gathered in a design tree with customizable driving parameters.

Conduct a RE activity based on heterogeneous data is a recent and new kind of knowledge approach ([Laroche 2008]). The technical characteristics of a product are extracted and saved in order to capitalize the associated knowledge.

2.2 The shape descriptors

Shape matching, retrieval and other technics based on shape descriptors are part of a well-covered scientific literature. It can be summed up as generating a key from a model which is sufficiently descriptive and discriminant to be used as a comparison criterion with other keys, for the retrieval from a database for example [Tung 2005].

Shape descriptors can be classified in 3 kinds of methods, as described in [Tangelder 2008]. In the feature based methods, the shape of a model is expressed by a d-dimensional vector of values. The values of this vector represent the features of the shape. A feature expresses properties of a geometrical and/or area of the shape. The vector can be seen as a high dimensional point. Comparing two models by that kind of method is equivalent to determining how close the two corresponding points are in the space of dimension d. Contrary to the previous purely geometric approach, the graphs based methods propose a descriptor with much meaning. Indeed, the idea is to describe how the different shapes of the studied model are linked together. The links are connectivity relations between the shape components of the model. Finally, we can consider a third category of methods, the geometry based methods. That kind of approaches is based on some specific geometrical properties of the considered component.

In the amount of shape descriptors, one of them seems to be popular in the current researches: the Reeb graph.

2.3 The Reeb graph

The Reeb graph (RG), as in [Reeb 1946], is based on the Morse theory. According to this theory, a continuous function defined on a closed surface can characterize the relation between the function critical points and the the topology of that surface. The Reeb graph is a graphical representation of a 3D model. It displays the surface connectivity between its critical points. The original construction principle is to apply the function on every point of a 3D model surface. A node is associated to each critical point and an edge between nodes represents the surface connected components between the critical points. The RG can be applied to 3D triangulated surfaces, the function is then calculated on the mesh nodes. RG are constructed in a discrete way. Intervals are defined on the range of function values. Each interval corresponds to one are several areas on the model surface. The number of intervals is sometimes called graph resolution. The graph is generated by creating a node on each surface area and by linking two nodes with an edge if they are surface's connected components. The resulting graph is a skeleton representation of the surface topology. The overall shape of the resulting graph depends of the choice of the function.

An interest of a graph is that it can be represented as a hierarchical graph. The comparison of 3D models is then simplified as a 1-dimensional problem which results in the comparison of two hierarchical graphs. The Reeb graph methods for shape matching are in the most cases based on that way, using some similarity computation functions from the graph theory literature. In figure 1, a RG of a connecting rod is presented.

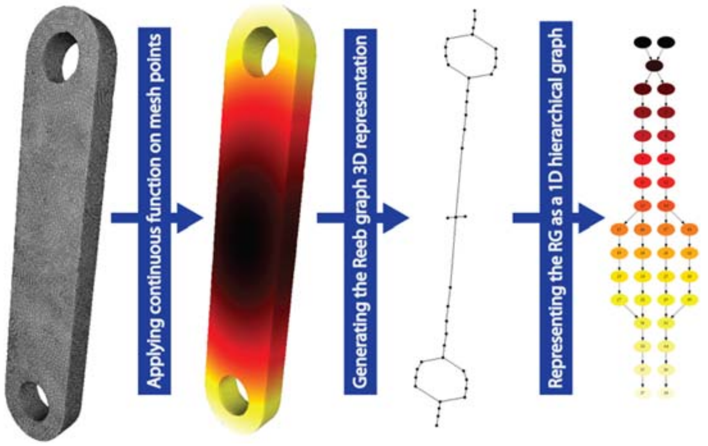

Figure 1. 3D and 1D representations of a Reeb graph of a connecting rod

Recent approaches of RG computing on 3D meshes are in fact an approximation comparing to the original construction. As it is based on the meshes' nodes, and not on all the points of the considered model surfaces, they result in approximated graphs. As demonstrated in [Biasotti 2003], they are still appropriate and perform well in the context of shape description. The authors also propose a review of several mathematical functions, each one with different evolution, different properties, and sensible to specific parts of the shape. That flexibility is another point of interest.

RG evolution proposes the addition of information into the graph nodes [Tung 2005]. From RG based on topology exclusively, derived RG are proposed such as aMRG (augmented **M**ultiresolution **R**eeb **G**raph). These approaches collect topological, geometrical and visual information as attributes. That addition provides better accuracy in the shape matching results and more consistency for the graph as a model descriptor. The multiresolution aspect facilitates the matching process with a granular structure enabling coarse-to-fine algorithms.

RG shape description methods are intended to be applied in computer graphics but have also been tested in a CAD context on solid models [Bespalov 2003]. The authors strongly believe that with some improvements, for example on the mapping function choice or on the sensitivity to topological features of the models, similarity detection would give more satisfying results.

2.4 Literature synthesis

In most of the previous works on RE, the attention is on a single component, apart from its environment, even though some wider scale consideration initiatives can be found. For example, [Chaperon 2001] assumes that it is possible to retrieve a CAD model from a scan of a complex system by extracting primitives. As a use case, the authors choose to work on retrieving the piping system of a large digitized industrial scene. The pipes are retrieved as cylinders using Gaussian images. But still, it focuses on a purely geometric approach. And the proposed approach is more appropriate to large industrial environments. The maturity management purpose is not treated in the literature. As a conclusion, the figure 2 proposes a context and state of the art synthesis.

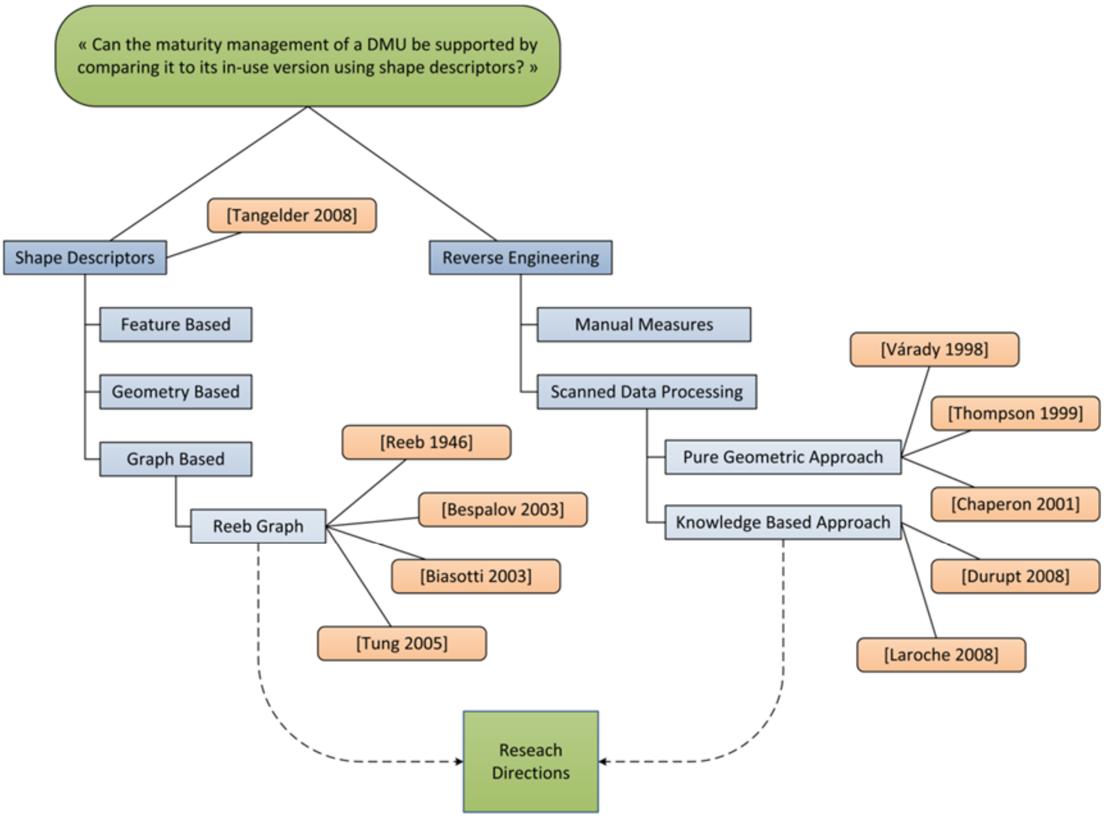

Figure 2. Graphical representation of the research question, the state of the art and the paper thematic

Our research question is: can the maturity management of a DMU be supported by comparing it to its in-use version using shape descriptors? That problematic is addressed by two kind of thematic directly connected. The first one concerns the shape description domain and the second one concerns reverse engineering thematic. In the literature, there is no RE approach based on shape description. Therefore, we propose to treat maturity management of DMU by addressing first RE approach for retrieving in-use models and second Reeb graph for shape comparison with DMU models.

3. Proposition of a research direction

In this section, research leads are presented and a methodology answering the DMU management maturity problematic is described.

3.1 Hypothesis and requirements

As seen in section 2, a user interactive approach is needed since the RE activities address topological, geometrical and functional information. In our hypothesis, the user is a DMU expert familiar with the product. Moreover, as the DMU is known, all its composing parts are sorted in a database, under the desired form and accessible by queries. The solution works on mechanical systems. By that, we consider systems with relative movements between their parts, the presence of kinematic links.

The real system may not be dismantled. As in classic RE approach, it is digitized by a laser scanning device. So, in our context, we consider two inputs:

- A meshed surface extracted from the DMU envelop,
- A meshed surface interpolated on the point cloud obtained by the scan of the real product.

Concerning the shape descriptor, we consider that the DMU parts are indexed as in shape indexing approaches. The index used is the shape descriptor and is evaluated with its characteristics ([Tung 2005]):

- Size (query speed),
- Fast generation,
- Affine transformations invariance: rotation, translation, scale factor,
- Mesh connectivity independence,
- Mesh noise independence,
- Coded information pertinence.

From these hypotheses, through the use of a simple use-case, we illustrate two limitations of the RG approach, described in the next section.

3.2 The Reeb graph limitations

Topological shape descriptors present some interesting characteristics. RG can be suitable in CAD context. The aMRG presented in [Tung 2005] are based on a mapping function. The authors use, on each point, a mean geodesic distance to all the other points of the triangulated mesh. That kind of function has a useful characteristic: it is relatively insensible to the pose of the considered meshed model. Here, a "pose" for a single model corresponds to the orientations and positions between the different components of the scanned in-use product. In figure 3, an example of the evolution of the mapping function over the points of two connected connecting rods in 2 different positions is presented. As shown, the evolution is similar within the two poses. This relative insensibility to the pose makes RG effective for describing a mechanical product.

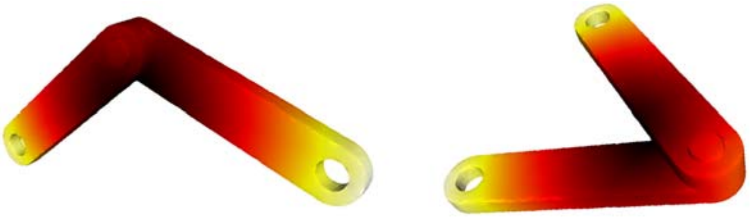

Figure 3. Evolution of the values on the mesh nodes of the mean geodesic distance as a mapping function on 2 connected rods in 2 different poses

3.2.1 The resolution of the RG

The resolution aspect of the Reeb graph can be a problem during the comparison process. At the same resolution, a part and a group of parts get graphs that are difficult to compare. The part is more "described" than the group of assembled parts. The figure 4 shows an example of this problem. At the same resolution, the single connecting rod RG (a) is composed of more nodes than the 3 connected rods (b). Actual matching algorithms are based on graphs structure comparison. They perform well for the original context of shape matching. But retrieving the single connecting rod as a part of the 3 connected ones is difficult with that form of graph. That problem is due to the resolution aspect of the RG which belongs to its generation parameters. Therefore, RG post-processing has to be determined for allowing graph comparison of a mechanism.

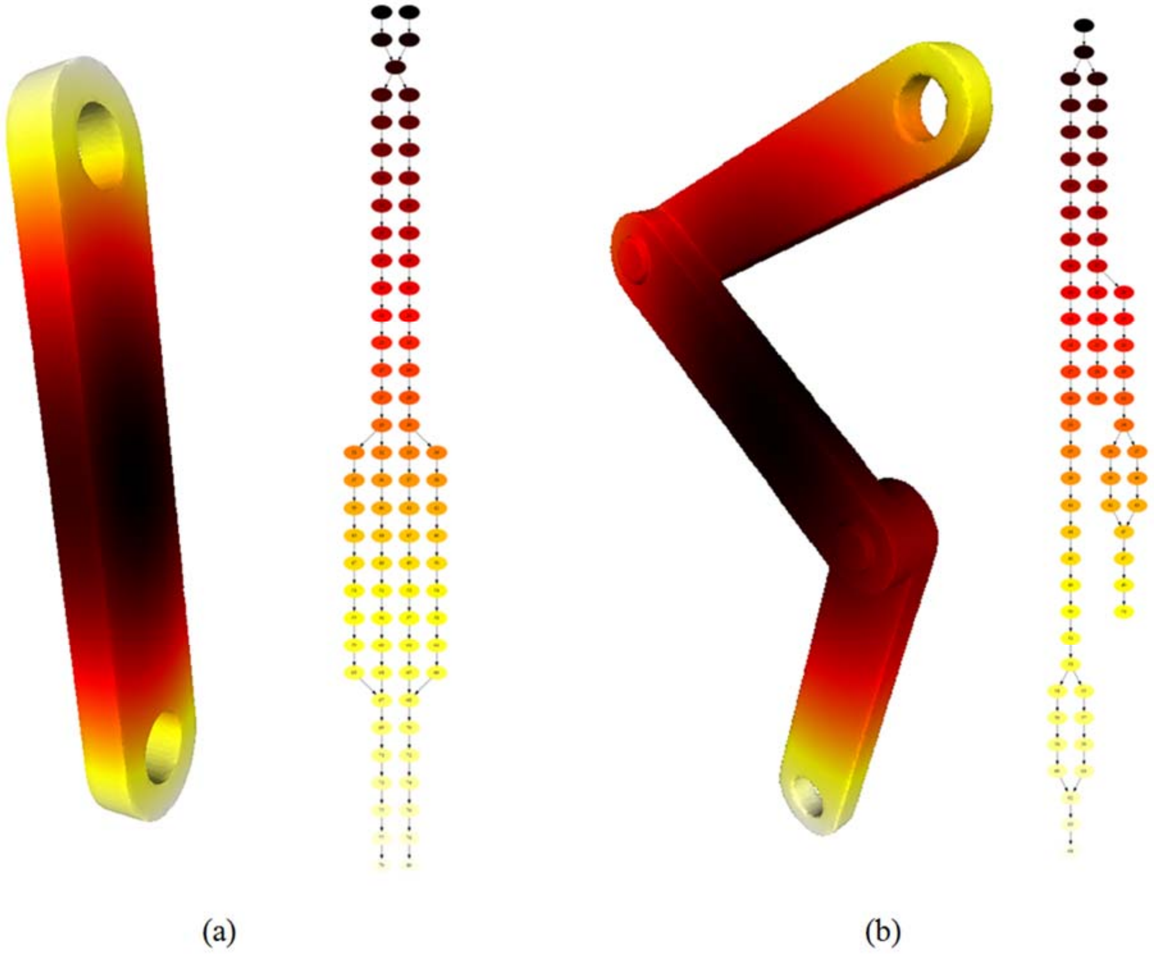

Figure 4. The RG for a single connecting rod with 80 nodes (a) and the RG at the same resolution of 3 connected rods with 64 nodes (b)

3.2.2 The external aspect of the RG

Digitize a group of assembled parts as a single part with laser scanning device implies some drawbacks. The resulting point clouds reflect the exterior envelop of the system. The internal contact surfaces between the different parts are not acquired. The notion of component does not exist in the RG generation context. By definition, the RG is generated on the external envelop of a 3D model. In other words, the RG, as we see it, of an assembly of components is not the "assembly" of each component RG. The figure 5 illustrates this phenomenon. The shape parts topologically identifiable are circled by rectangular forms. The undefined areas are circled by ellipses. They correspond to simple branches in the RG.

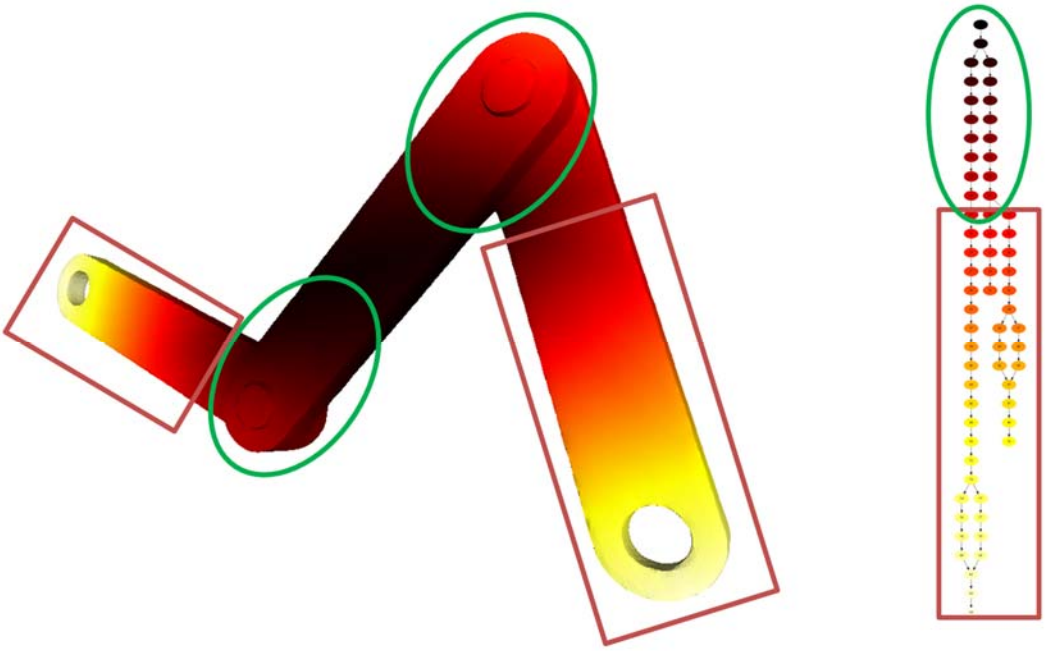

Figure 5. Example of a 3 assembled connecting rods 3D Reeb graph (a) and its 1 dimension corresponding graph (b)

3.3 Lead proposition

Using RG "as is" is not an efficient way to describe a mechanical system in DMU context: non-topological or non-geometrical information are not managed. Therefore, it is clear that the RG must be enriched with information that does not only belong to the topology and the geometry. The paper does not propose this enrichment but assumes that this enrichment is enabled. The proposition focuses then on the description of the methodology used for playing the scenario of DMU management maturity based on RE and DMU.

Our research direction consists in describing and characterizing a mechanical system by its relative movements. As a matter of facts, it is often a requirement for calculating product characteristics such as efforts, speeds or paths. As we consider mechanisms, the considered products should have possible movements. The representation of the links between groups of components in our scenario will therefore be based on the kinematic chain. The kinematic chain is part of the knowledge embedded in a mechanism. In our simple use case of 3 connected rods, the kinematic chain is composed of 2 mechanical links: 2 revolute pairs. As shown in figure 6, the kinematic chain brings some information where the topological description is not useful. The kinematic pairs correspond to undefined zones of the meshed scan data.

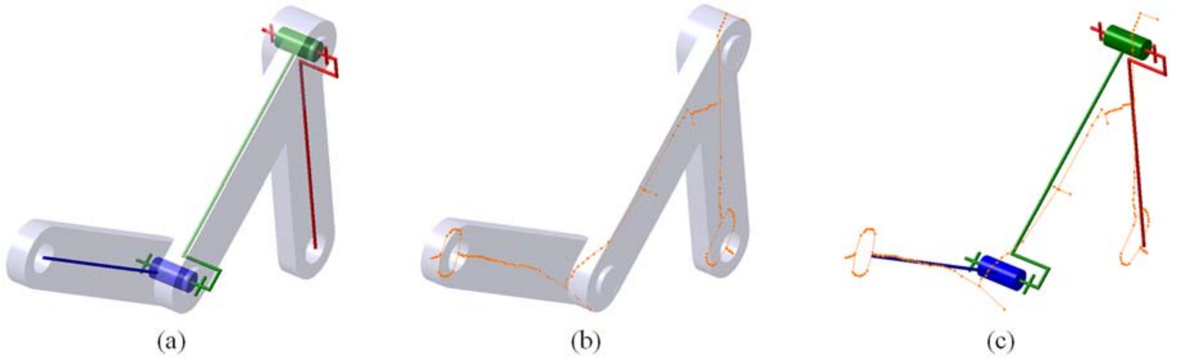

Figure 6. The kinematic chain of 3 connecting rods (a), corresponding Reeb graph (b) and the 2 graphs stacked up

We assume that using such kind of complementary information based on knowledge as additional criteria is a lead to perform an effective DMU maturity diagnostic. A typical process scenario is shown in figure 7: a workflow illustrating the part recognition support in a meshed digitized as-build product.

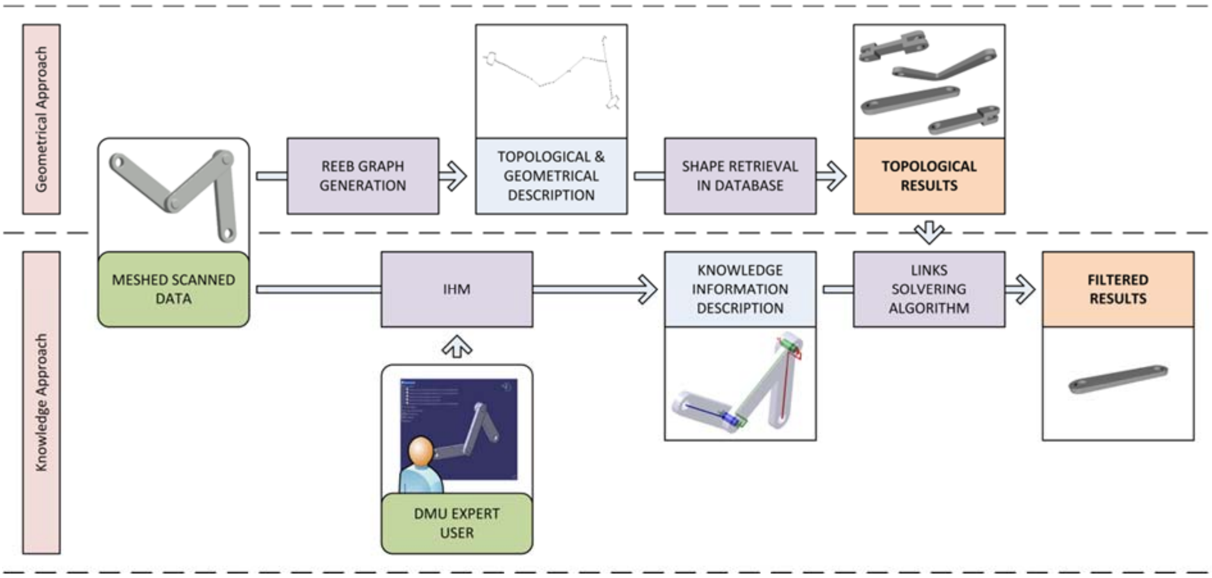

Figure 7. Example of process workflow based on Reeb graphs and integrating knowledge information

In this process, we assume that a previous comparison has been made. The similarity between the digitized in-use product and the DMU envelop denotes a possible presence of differences. The current activity is to determine which parts are present and which are not, based on the **B**ill **O**f **M**aterials (BOM), extracted from the DMU.

Topological Approach. First using the mesh RG, potential suitable parts are retrieved from the database. The database contains components indexed by their RG as it is done in shape retrieval methods. The identification criterion is topological with linked geometry. Components' graphs may be identified as mesh subgraphs. Some mesh subgraphs may be identified as only subparts of components, due to lack of information. The RG matching process gives an approximate location for each retrieved component. All retrieved components are purely topological results stored for the second part of the process.

Knowledge Approach. Then, with an interactive interface, the expert user adds knowledge information on the mesh. In this case, the user generates the kinematic chain, identifying kinematic links and mesh areas corresponding to their location. Using that new information, a linkage matching algorithm is executed with two inputs: the list of potential suitable parts and the kinematic chain. On each defined pair, based on the functional surfaces of each potential component, the algorithm determines a filtered list of potential parts. The principle is to determine the matching pairs among closed identified parts based on their functional surfaces allowing to insuring the defined kinematic pairs (figure 8). For example, a revolute pair needs can be construct with two parts with a cylindrical surface and a planar surface in its functional surfaces. In case of multiple possible solutions, the user decides the one that fits the best.

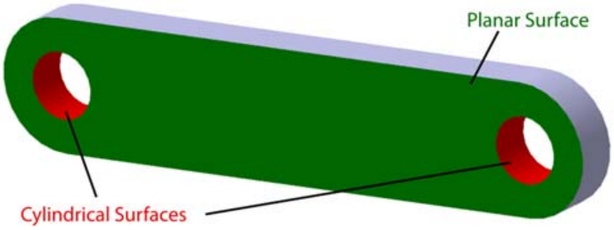

Figure 8. Example of functional surfaces on a connecting rod

The filtered parts are then located in the mesh with the approximated locations previously identified. Finally, the algorithm emphasizes areas without corresponding parts. These areas correspond to part changes (because of a different geometry or a lack) so maturity defaults.

As a parallel way of research, the attention is also focused on the RG resolution problem. Indeed, it is important to enable the post-processing of RG for enabling its use in the context of DMU maturity process. We propose to simplify the RG by merging the nodes on the same branch of the graph with only one input edge and one output edge. The attributes of the merged nodes are also merged. That approach does not affect the topological consistency of the shape, the merged nodes are poorly descriptive nodes caused by longitudinal part of the associated shape. An example of the simplification is displayed in figure 9.

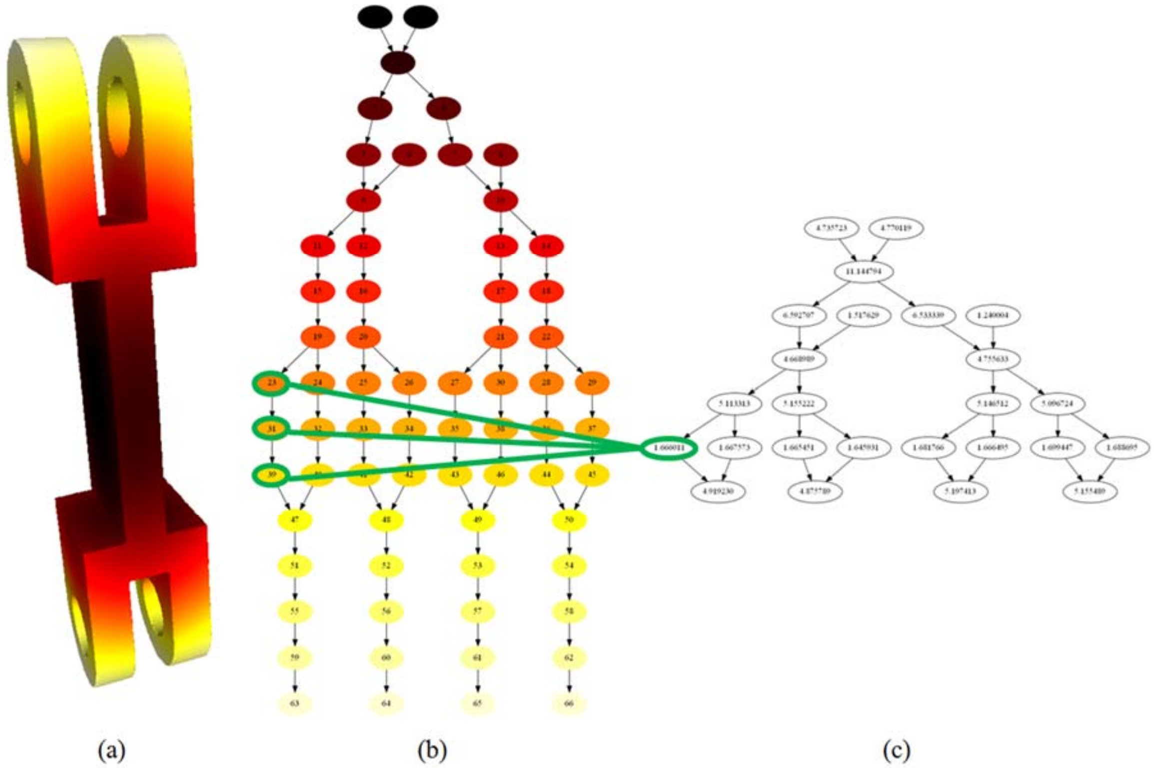

Figure 9. RG simplification for a connecting rod (a): the original RG (b) and the simplified graph (c). In bold, an example of branch simplification

4. Conclusion

DMU maturity management is an unsolved matter for long lifetime products. RE approaches exist but are focused on single components. In this paper, we focus on using Reeb graph shape descriptors to support the comparison of an in-use product with its original DMU. RG are powerful shape representation in a pure topological and geometrical context. Still, Reeb graph are not suitable to be used "as-is" in the context of an assembly. Therefore, we propose to adapt the Reeb graphs to make them more product-oriented. Meanwhile, we propose to enrich Reeb graph with the related product knowledge for achieving the management of maturity defaults. The process is based on retrieving the matching parts between the virtual representation and the real product. After the identification of the matching parts, the result is presented in an expert application (DMU or CAD) and is directly enriched by the user. This methodology will be tested with further examples. For now, it presents interesting issues in the domains of heterogeneous data integration but requires a powerful knowledge-based solution for enabling the user interaction. To conclude, the aim of that method is not limited to mechanism but is opened to a wider range of systems as mechanically welded structures (ships, plants) or large-scale assemblies (aircrafts, power generators, etc.).

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