Liaison-Based Enriched CAD Model Representation for Assembly Tasks

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Abstract. In mechanical engineering, the analysis and evaluation of CAD models of the final assembly are largely exploited to address complex assembly tasks to enhance the production process. However, CAD models definitely include geometric and topological information on parts, while the availability of additional important information, such as the semantics of parts, is not given for granted and is manually provided. This work aims at defining an enriched CAD model representation to integrate and provide product and assembly process information in a unique model to be exploited as input in assembly tasks. The representation is based on a new data structure, denoted as liaison, which is meant to comprehensively express the relation between two mating parts of the assembly. First, the key elements characterizing a liaison are pointed out, which are both geometric and semantic data regarding the assembly's parts and their relations. It is underlined that all the information stored in the proposed liaison-based representation is the outcome of a process that automatically extracts data from the product boundary representation as created/exchanged by commercial CAD systems. Then, the the paper describes the process to define and compute the list of liaisons, and thus returning the enriched CAD model representation. Finally, the developed interface for inspecting the automatically created enriched CAD model representation is discussed as well as possible applications to strengthen the potential of liaisons in optimizing assembly tasks.

Keywords: CAD assembly, CAD model representation, Liaison, Semantic Information, Engineering knowledge
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1 INTRODUCTION

In the last decades, mechanical engineering sector has been largely affected by the advent of digitalization and the increasing potential of technologies to automatize the various production phases. In particular, the

production of mechanical assemblies usually relies on the use of a digital model of the final product to analyze, plan, and simulate complex manufacturing operations, avoiding waste of material, as well as reducing time and costs [10].
The availability of a consistent and expressive digital model of the final product results thus a crucial condition that enables both a beneficial use and integration of the different technologies and the achievement of optimal and feasible results from the modeling, assembly planning, and reuse standpoints.

For this purpose, the representation of the 3D model of a real product is commonly provided through commercial Computer-Aided Design (CAD) software by means of which the geometric and topological properties of the components of an assembly are ensured. However, especially when dealing with industrial CAD models of mechanical assemblies, the inclusion and availability of semantic information, i.e. all the non-geometric information, such as category membership, technological data, and functionality, is not given for granted [13]. Also, due to the gathering up of different design conventions, components belonging to same class can be modeled according to different criteria, or vice versa, components belonging to different categories can be quasi-identical in shape, and this generates misleading situations. Moreover, parts can be missing, or else purposely omitted (e.g. fasteners), making even more challenging the parts relations understanding.

According to the above considerations, before actually algorithmically addressing assembly tasks, a first CAD model processing phase is required to infer the necessary data associated with components and their relations and interpret the assembly from the engineering point of view. Performing a complete data extraction is not trivial and usually most of the analysis is limited to low-level information detection (e.g. existence of contact, presence of features, etc.), while high-level information (e.g. type of connection, functionality of parts, etc.) is often neglected or manually provided by experts. This, on the one hand, limits the use of engineering meaningful data, which instead would affect the CAD model management, on the other hand, avoids the automation of the assembly tasks performance.

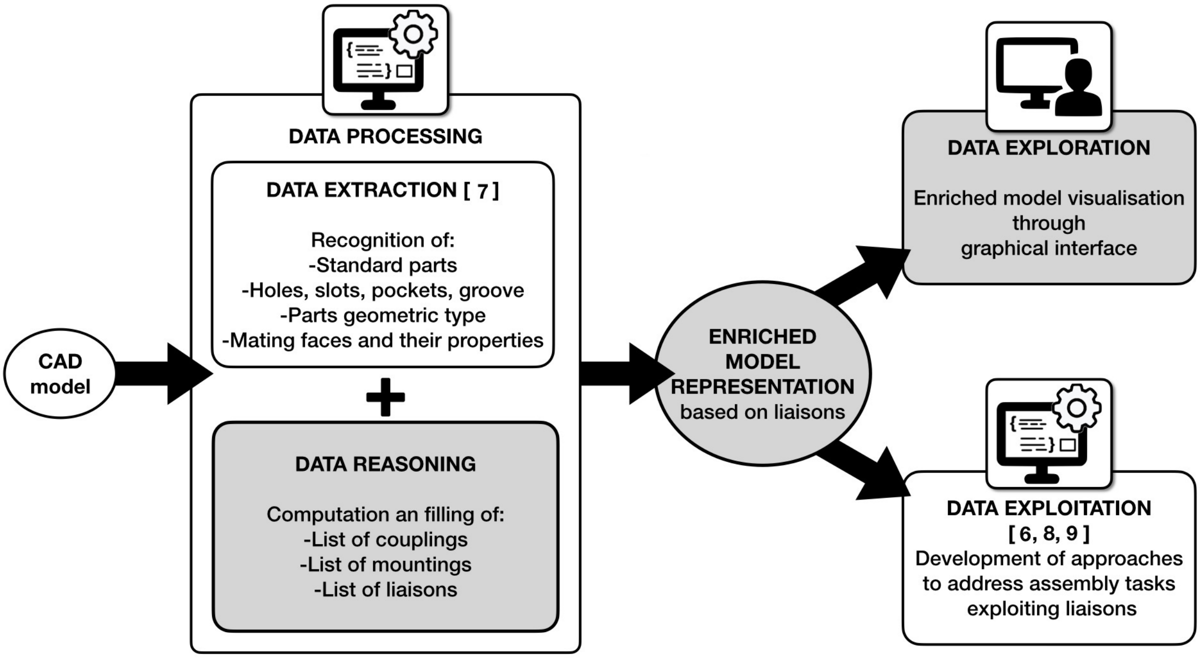


Figure 1: Main components of the under development tools supporting assembly related tasks.

Therefore, it results innovative and very useful the development of a comprehensive and standalone system capable of combining both the needs, i.e. the automatic extraction of high level semantic information from a CAD model and their usage in assembly tasks.

The authors' research is placed in this context and aims at automatically extracting from CAD models of mechanical assemblies high-level semantic information and, then, leveraging it to address assembly tasks. Figure 1 provides an overview of the main components of the developed system highlighting the automatic processes and the module devoted to support human inspection and evaluation. This paper focuses on darker grey modules in the figure. In detail, at first a processing of the CAD data is carried out. It consists of a data extraction phase and a data reasoning phase, which respectively analyze parts' geometry to recognize some meaningful classes of components and relevant features, and then enhance the semantics of the extracted data by defining and generating the liaisons elements, characterized by the way in which components are put together. All data processing steps are performed automatically through developed algorithms. The returned output is an enriched model representation that can be both browsed and inspected by experts to visualize the information via a graphical interface, and used as input of computer-aided tools to address assembly tasks in an innovative way.

One of the key features of the work, which is the focus of this paper, is the definition of the enriched CAD model representation collecting the semantic data. In particular, a crucial point is in the definition of a data structure, called *liaison*, able to comprehensively express the relation between two mating parts of the assembly, both from the geometric and the engineering point of view.

In the following, first, a brief overview of the structures usually adopted for storing information about CAD model's parts relations is reported in Section 2, pointing out the need for a more comprehensive and engineering meaningful one. Section 3 provides the main concepts and the key data that stand at the basis of the liaison structure, which are automatically extracted through the authors' system. In Section 4, then, the definition of liaison and the computation process automatically creating the enriched CAD model representation are described, highlighting their distinctive properties. Finally, Section 5 shows the developed interface for an intuitive visualization of the enriched CAD model and inspection of its elements. Finally, the Conclusions section discusses the advantages in using the liaison data structure and possible application are provided.

2 CAD MODEL REPRESENTATIONS

When importing a model of an assembly in standard format in an ordinary CAD system, usually the only information that is definitely available is the set of the parts, represented by means of their topological and geometrical entities [22]. The assembly's components can be typically arranged according to a hierarchical tree, where parts are grouped in subassemblies respecting some parent-child relationships or in groups that follow some logical criteria (e.g. same material, same function, same mounting technique, etc.), or else they can be all at the same level, like in a list. However, the existence of the grouping and its characterization depend on the designer choice and on the importing/exporting operations. It is, thus, not necessarily reliable and meaningful in the engineering sense [19]. In addition, this representation does not explicitly describe the contacts between pairs of parts and their properties. These might be implicitly contained in the CAD tree structure, but they must be computed by means of surfaces or volumes proximity evaluation to be available. Also, parts' type and the functionality are unknown, unless some names may refer to them or else codes are added as descriptions, but it is not mandatory, no universally adopted naming conventions exist and human intervention is needed to insert and interpret them.

In this context, the automatic enrichment of CAD models with semantic information gained much interest in the last years. A great effort has been made in the enhancement of the product modeling process to represent product knowledge and technology information [17]. It results a crucial step to improve product knowledge exchanging and sharing [1]. Several works can be found in literature that are focused on that topic and address it under different aspects. Some aim to mitigate the semantic gap by providing functional semantic annotation methods for CAD models based on ontologies (e.g. [4, 15]). Some others, instead, are more focused on the recognition and extraction of specific engineering knowledge implicitly contained in the geometry of CAD models (e.g. [11, 12, 16]). However, the semantic interpretation of CAD models and the leverage of high-level information are still open issues that deserve to be further investigated. In fact, in many applications the only geometric and topological data are still used, or semantic information, such as parts types or assembly features are manually provided by experts and this strongly affects the production process, in terms of goodness and reliability of results, amount of required resources, time, and costs.

In addition, once the data is extracted, it is rarely referred to the definition of specific structures aimed at collecting and providing all the types of data inferred, both relative to the single components and the relation between two or more parts, in a meaningful manner that can facilitate their exploitation in assembly-related tasks. For this purpose, common strategies are found in literature to represent the relationships and the constraints between the parts of an assembly by means of matrices or graphs [23].
As for the first case, the mostly adopted matrices are of three types, and can be found with different names. That is, Adjacency/Contact/Liaison Matrix, where the value of element expresses the existence of the contact between two parts. The value is generally 1 or 0, but in some cases the matrix can be transformed by considering the contacts according to the three axes x, y, z separately and making the matrix elements 3-digital arrays [5]. Constraint/Collision Matrix are instead defined to represent obstructions between two parts when moved along a given direction [18]. Finally, Stability Matrix can be used to provide a stability value of contacts mainly associated with the type of fastening between any pair of components [3].
The content of the above matrices can be equivalently stored in graph structures. Each assembly part is a node of the graph and the information extracted from the CAD model are included in the edges and in their attributes. The standard graphs employed are of two types. Namely, the Liaison Graph is the representation of contact information between any pair of parts, corresponding to the Adjacency Matrix [21], while Blocking/Precedence Graph, similarly to the Constraint Matrix, provides information about the blocking relationships within a component for a given direction (mainly the x, y, z axes) of assembly [2]. Graphs can be enhanced, for example, making them weighted graphs [24], and, in the simplest case, weights are given by the type of contact and represent the same data expressed by the Stability Matrix. Also, graphs can be enhanced by adding additional information related to the type of the elements and of the blocking conditions among parts. For instance, in [25] a connector-based relational model (CBRM) graph is provided, which allows to represent an assembly integrating both geometric and non-geometrical assembly data. In particular, *components* and *connectors* are distinguished, in order to take into account the functional meaning of mating features and mechanical elements providing constraints in the assembly analysis. However, the classification of parts as connectors and the mating information are manually given in input and the model representation is not automatically carried out. Or else, in [16] the Enriched Assembly Model (EAM) is presented, that is an attributed graph that encodes different level of information, such as the hierarchical assembly structure, the relationships between pairs of parts, shape properties of the parts, and some statistical evaluation of the previous three types of data. Anyhow, in all the cases no indications on how the elements can be assembled together are provided, such as using "simple" component coupling or through specific mounting which can indicate more stable placement, as proposed here.
These structures have aroused great interest over the years because they can be managed as computational objects and then given as input data to algorithms. However, the weaknesses in that assembly representations are several. First, when dealing with assemblies made of hundreds of parts, matrices and graphs have big dimensions and the increase of computational time and costs is the immediate consequence. Secondly, matrices are too abstract structures that can not comprehensively describe the contact between two parts, both from the geometric and engineering point of view. Moreover, in general, the data stored are not at all intuitive to read for the concerned experts, since even high-level information is associated with a numerical value (i.e. items of the matrices or weights of graphs' edges).

To overcome the limitations, the paper presents a new semantically enriched product model representation for mechanical assemblies. The key idea is to enrich and organize the original CAD model as a list of elements defined as *liaisons*, each of which identifies a couple of mating components. It is to underline that, in general, the term liaison refers to the simple contact between the components but, in this case, the liaison concept is intended in an extended way, more similar to [20]. Namely, a liaison is defined as a new data structure that totally expresses the relation between two mating parts of the assembly. That is, a liaison provides high-level semantic information concerning multiple aspects, from the geometry of the contact (e.g. type of contact faces, common axes, percentage of covered surfaces, etc.) to the assembly process features (e.g. mounting features, presence of connection elements, etc.). In the following sections, the differences between the here provided liaison structure and that of [20] will be further discussed.

Before going deeper in the liaisons and the enriched CAD model computation, some preliminary concepts are now introduced, the understanding of which is crucial for the discussion.

3 PRELIMINARY CONCEPTS

Since the authors' research main goal is the development of a comprehensive system that can manage the model of a mechanical product and evaluate it for different assembly tasks, the only data given as input is the CAD model of the product. Not to be constrained by any specific CAD system, only the B-rep of the assembly's parts and their position in space are known. As a consequence, an automatic data processing phase is carried out, exploiting the geometric and topological information relative to parts to automatically evaluating parts' relations, as well as their semantics related to their engineering meaning [7].

The main information automatically extracted and required for the liaison definition and their properties fundamental in the semantic interpretation of a mechanical assembly are discussed in the following.

3.1 Information Relative to a Part

Feature A feature is a local information associated with a part.
In detail, a feature is intended to be a concave portion of a part forming a specific shape. A large variety of features exists in literature, but the focus of the work is on a limited set of features, that are holes (Fig. 2a), polygonal, rectangular and circular-end pockets (Fig. 2b), slots (Fig. 2c), and grooves (Fig. 2d). This choice is given by the fact that the listed features have an intrinsic engineering meaning crucial for the assembly interpretation. As a matter of fact, they can be associated with typical seats for mechanical parts (e.g. threaded holes, keyways, keyseats, O-ring seat, etc.).
Their presence, together with the evaluation of their characteristic dimensions are automatically obtained exploiting an existing recognition system.

Standard parts and fastening sets Standard parts are those obeying international norms in shape and dimensions (i.e. associated with codes UNI, ASME, DIN, ISO, etc.). Standard parts have a precise role within the assembly, often related to connecting, blocking or spacing two or more components. As a consequence the awareness of these types of parts is crucial for the semantic interpretation of a CAD model.
In addition, making reference to how they are used in reality, some of the categories of standard parts can perform their function if combined with other categories. This is the case of threaded fasteners, such as screws, nuts, washers, and studs. As a consequence, the concept of fastening set is introduced, according to which coaxial fasteners in contact with each other are grouped in a functional set. This because all these components together perform the mounting function, while considered individually they have a less precise semantics.

In [7] a method is presented for the automatic detection of parts belonging to some categories of standard parts. In particular, the following eight categories are considered: screws, nuts, washers, O-rings, keys, circlips,

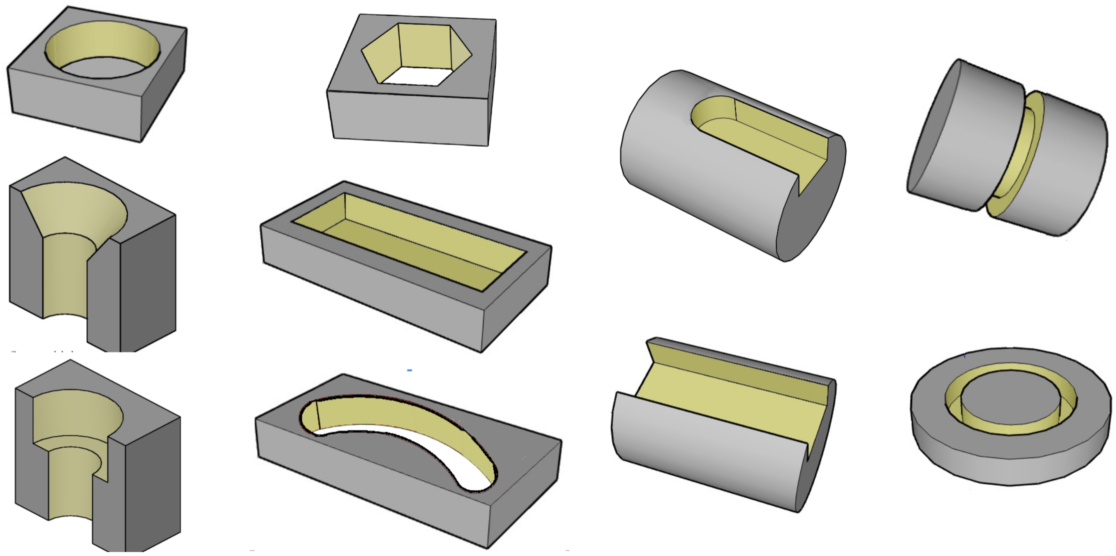


Figure 2: Examples of considered features.

studs, and pins. It is to underline that the algorithm not only returns for each standard part the category of membership, but also the subcategory and the typical engineering dimensions.

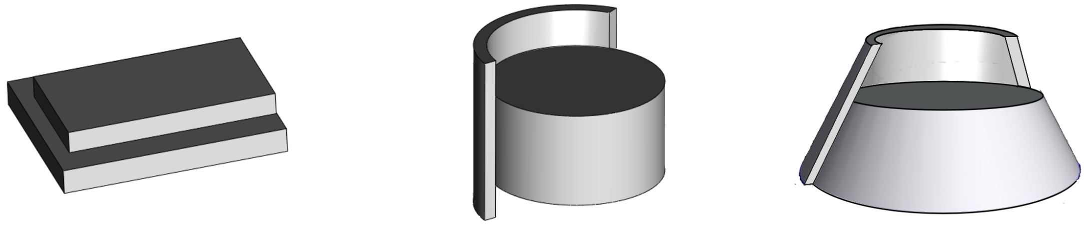
Custom designed parts Custom designed parts are the set of parts that do not fulfill published and uniquely identified standard specifications. These, in fact, are modeled and sized depending on the structure and purpose of the assembly. It is assumed that custom designed parts mainly constitute the supporting frame of an assembly (e.g. chassis, covers, crankshafts, boxes, etc.).
In the CAD model processing, all those parts that are not recognized as standard are denoted as custom designed.

3.2 Information Relative to Parts Relation

Coupling A coupling identifies the existence of a contact between two parts of an assembly. More precisely, given two parts P_1 and P_2 of an assembly, a surface contact between a face f_1 of P_1 and a face f_2 of P_2 is called *coupling* and it is defined as $c(f_1, f_2)$.
A coupling can be planar, cylindrical, or conical according to the geometric type of the faces in contact (Fig. 3).

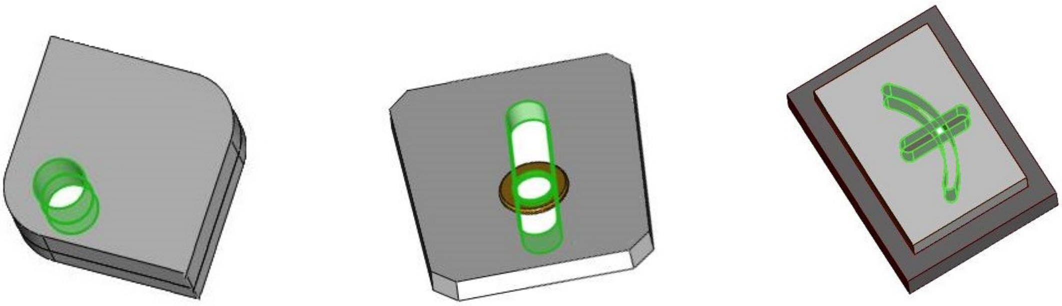
The data processing phase returns the list of all the couplings identified in the CAD model by means a contact detection process that, for each pair of faces belonging to different components of the assembly, analyzes the surfaces' relative position. In addition, all the information associated with the two mating faces is included in the coupling and has readable properties. It comprises, for instance, the parts P_1 and P_2 to which they belong, their orientations and relative positioning in the space, the surface contact type, and the surface contact area.

Mounting A mounting is an attribute of coupling. In particular, it identifies the existence of two coaxial features each having a border lying on one of the two mating faces that define the coupling. That is, given



(a) Planar. (b) Cylindrical. (c) Conical.

Figure 3: Examples of couplings.



(a) Hole-hole. (b) Hole-pocket. (c) Pocket-pocket.

Figure 4: Examples of mountings.

two parts P_1 and P_2 of an assembly, and assuming the existence of a coupling $c(f_1, f_2)$ between the planar faces f_1 of P_1 and f_2 of P_2, the existence of two features, each having a loop of edges lying respectively on the faces f_1 and f_2, is called *mounting*. It is defined as $m(f_1, f_2, F_1, F_2)$, with F_1 and F_2 the list of faces of the features of respectively P_1 and P_2 (Fig. 4).

Similar to couplings, also mountings are automatically identified during the data processing phase. In particular, for each planar coupling, the list of all the mountings, when they exist, is returned by means of the evaluation and matching of the features associated with the part of the coupling.

All significant and useful information associated with the faces involved in a mounting are stored as properties and are accessible. Besides the parts P_1 and P_2 to which they belong and their orientation and relative positioning in the space, the general dimensions of the mounting features (e.g. depth and minimal width) are reported, as well as a flag that indicates if the features are aligned with each other (e.g. the centers of two holes coincide, the center of a hole is on the central curve connecting the ends of a slot) or, in the case they are not aligned, the value of their axial misalignment.

4 LIAISON DATA STRUCTURE

Based on the above definitions and concepts, the liaison data structure can be now discussed in detail. In the following, the liaison's key features are pointed out, along with the computational aspects.

4.1 Definition and Properties

Given two parts P_1 and P_2 of an assembly, such that P_1 and P_2 are custom designed parts and at least a coupling exists between P_1 and P_2, the liaison between P_1 and P_2 is defined as $l(P_1, P_2, C, M, S)$, where :

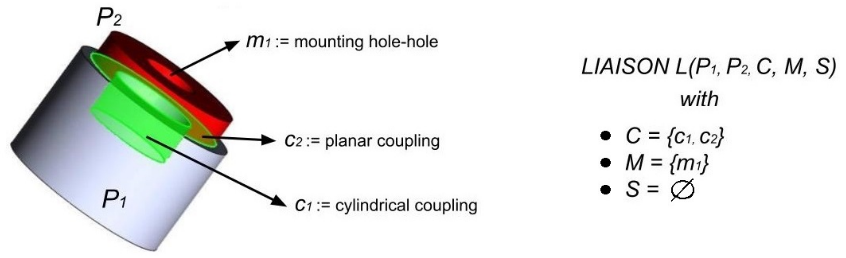
- $C = \{c_1, \ldots, c_r\}$ with $r > 0$ is the list of couplings between P_1 and P_2;
- $M = \{m_1, \ldots, m_s\}$ with $s \geq 0$ is the list of mountings between P_1 and P_2;
- $S = \{s_1, \ldots, s_t\}$ with $t \geq 0$ is the list of standard parts and fastening sets connecting P_1 and P_2.

The presence of a list of couplings, and not a single coupling, is justified by the fact that multiple faces in contact can clearly exist between a pair of parts, one for each couple of colliding faces (e.g. Fig. 5a, Fig. 5b, Fig. 5c, and Fig. 5d). Thus, in the liaison object a list of all the identified couplings is stored. As already said, each coupling c_i contains the references to a couple of mating faces and thus, to all their geometric characteristics.

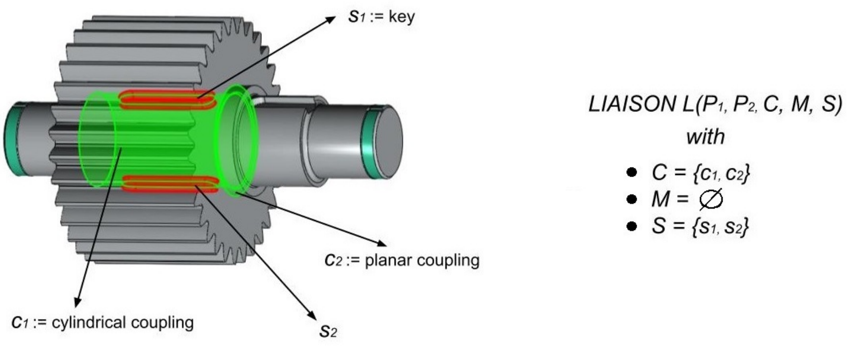
This can be mentioned as one of the features that distinguish liaisons and encourage their use to describe an assembly and the relations of its parts, instead of the conventional matrices or graphs. In fact, matrices simply report the existence of a contact between two parts, or at most can estimate the existence of the contacts according to the three orthogonal directions (i.e. along the x, y, and z axes). Graphs, instead, can contain information as attributes of nodes and arcs, but in a less intuitive manner. Moreover, in general, information regarding the number of faces in contact and their type is rarely given, which is extremely restrictive and unrealistic from the perspective of how the contact should be interpreted. Also in [20] this aspect is not totally addressed. In fact, Swain et al. define a liaison as a set of faces in contact between two parts, but only a limited number of situations are considered. For instance, only planar couplings' features are investigated and interpreted, while the process information included in cylindrical couplings is not treated, as well as the possibility to combine planar and cylindrical couplings. As a consequence, a comprehensive understanding of the relation between two parts is avoided. On the contrary, the availability of all couplings associated with the same pair of parts and accessibility to their data ensures a more in-depth description of the contact. The knowledge of the number of mating faces (i.e. the number of couplings), their geometry (i.e. planar, cylindrical, conical) and orientations (i.e. common axes for cylindrical and planar faces, normal vectors for planar faces), as well as the overlapping area extension, allows to infer meaningful information on the level of relative clamping between the parts, the degrees of freedom and possible movement directions.

Similarly, a liaison also includes a list of mountings, since more than one mounting can be identified between two contact faces (Fig. 5c) and, moreover, for each liaison mountings lying on different couplings can be found (Fig. 5d). Also in this case, the data relative to each mounting are contained in the m_i. The list M is another key element of a liaison, that considerably improves the description of a CAD model by giving engineering sense to the contacts between parts and that is generally overlooked. As a matter of fact, it is important to underline that a mounting is not only a topological attribute of a contact, rather it conveys a deeper semantic meaning. From the engineering point of view, the existence of coaxial holes, in fact, is a typical situation of parts mounted by threaded fasteners or pins. Thus, the presence of mountings results in a crucial feature to understand components' relations and to enforce their connection properties, as well as deducing the assembly process. Usually, the mountings analysis could be considered a redundant operation to deduce the assembly by threaded fasteners, since the presence of the fasteners is enough explanatory. When dealing with industrial CAD models, which can be affected by the issue of missing components, the knowledge of mountings nevertheless results fundamental being the unique way that allows to infer the presence of the not modeled fasteners. The accessibility to mountings' properties, such as their number on each pair of faces, their relative positioning, as well as holes diameters specifications further make reliable the assumption.

Standard parts as well can be multiple in a liaison (e.g. Fig. 5b, Fig. 5c, and Fig. 5d), and this is why the list S is provided. Each item s_i of the list can be both a single standard part or a fastening set (e.g. screw-nut-washer), in order to enhance its meaning and its role within the liaison. In both cases, all the information



(a)



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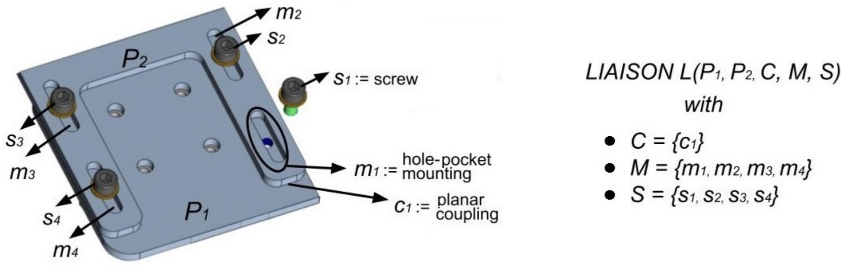
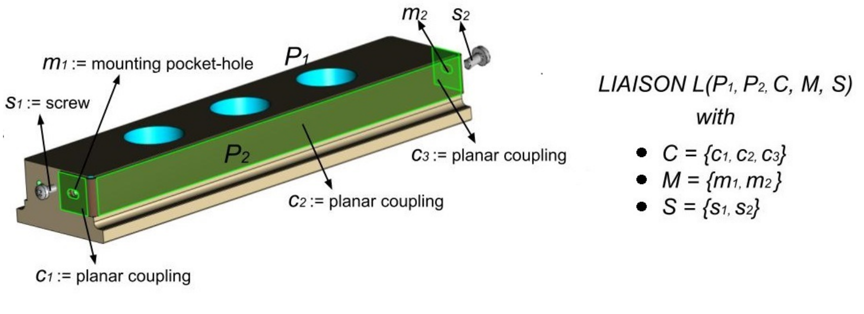


(c)



(d)

Figure 5: Examples of liaisons.

(e.g. category and subcategory) and dimensional values of the standard parts, along with their orientation and positioning, are accessible form each s_i. Moreover it also provides the access to the information if the standard parts included in S are all instances of the same subcategory (e.g. a collection of screws belonging to the same subcategory and having same dimensions) or belong to different categories. It is evident that this knowledge stands at the basis of a comprehensive high-level interpretation of the relations between two custom designed parts. For instance, the presence of a specific collection of fasteners joining two components along a given pattern not only suggests the assembly operation carried out, but also the tools needed, and the direction of extraction/insertion, as well as the path according to which they are mounted. Or else, the presence of a key allows to deduce that the two custom designed parts are respectively a shaft and a rotating element.
In summary, considering standard parts as an attribute of contacts rather than treating them like any other component results an innovative idea. It definitely distinguishes the liaison structure defined in this work from that presented in [20], which does not address this meaningful aspect, and does not actually mention the possible presence of standard parts. In addition, the choice of differently manage standard parts is beneficial in a number of ways. First, it has a strong semantic value, but it also promotes the use of the liaison structure for CAD model reorganization in relation to the computation and the intuitiveness. In fact, thinking of the liaison list as the collection of all pairs of contact parts, it would indeed contain too much elements when dealing with assemblies made of hundreds of parts, and thus its usage would not be advantageous in respect with matrices or graphs. However, as standard parts are in general a substantial portion of the total parts of an assembly, omitting them from the parts that can underlay a liaison consistently reduces the final number of liaisons in the list, making it easy to handle. It is known that starting from the similar aim of reducing the dimensions, there are methodologies that remove the fasteners from the contact matrices and then consider them later (e.g. [5, 14]). Nevertheless this type of approach is targeted at fasteners only, usually manually detected, while locating components are overlooked. Also, this does not allow to fully exploit standard parts semantic meaning and intuitively visualize their function within the mating relation, as is instead done when using liaisons.

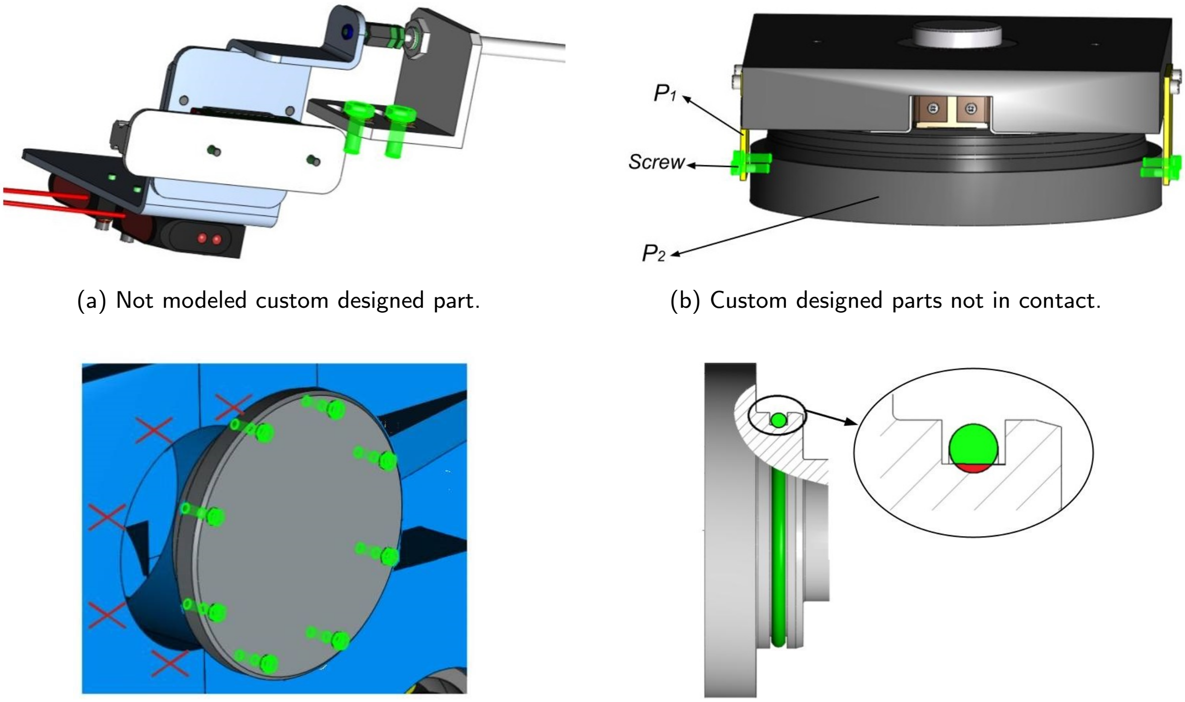
In Figure 5 examples of liaisons are provided to better visualize their characteristics. The first liaison (Fig. 5a) consists of a pair of axisymmetric parts with common axes, two couplings and a mounting. The knowledge of the geometric type of the parts and the existence of both a planar and a cylindrical contact allow to infer that the two parts can not slide freely with each other, rather they are blocked in one direction, that is relevant in the assembly process. The second case (Fig. 5b) shows a typical liaison between a shaft and a gear. It has two couplings and two standard parts, i.e. the keys, but no mountings. The awareness of the keys and their positioning in a keyway and a keyseat is crucial to understand the mechanical meaning of the two parts underlying the liaison and the fact that their relative rotation is avoided. The third example (Fig. 5c) shows a liaison characterizing two parts mounted by fasteners. The liaison includes only one coupling, i.e. there is a single planar contact between the parts, but there are four mountings, each given by the alignment of a hole and a pocket, and four standard parts. The presence of multiple mountings already suggests the fact that the parts are tightened through fasteners, then the knowledge of the screws inserted in them strengthens and confirms the assumption, allowing to interpret the contact from the engineering standpoint. Moreover, the common orientation between all the mountings hints the direction of their axes as the assembly direction for the two parts. Finally, the fourth liaison (Fig. 5d) provides a second example of parts mounted by fasteners. In this case there are two mountings given by the alignment of an hole and a pocket and the two associated standard parts, along with three planar couplings. The existence of two opposite planar couplings and lying of the mountings on them suggests that parts can not be assembled in the direction of the axis of the mountings,since they are blocked, rather an orthogonal direction would be preferred.

4.2 Liaison Computation

According to the definition given in Section 4.1, a liaison is between two custom-designed parts in contact, and for each pair of these there exists at most a single liaison. Thus, the developed methods for the automatic creation considers the list of couplings at first. Each coupling element is representative of a pair of faces in contact belonging to two general parts of the assembly. Given a coupling $c_i(f_1, f_2)$, the membership of the associated parts P_1 and P_2 in the custom designed parts is evaluated. In the affirmative, a liaison $l(P_1, P_2, C, M, S)$ is created and the coupling c_i is added as item of the list C of the couplings associated with that liaison, while the lists M and S remain empty. This happens unless a coupling between two different contact faces of P_1 and P_2 was already found and thus a liaison identified by the two current parts already exists. In the latter scenario, only the coupling c_i is added to the list C.
The examination is repeated for each coupling, and at the end of the process all the defined liaisons are collected in a list L. However, for each liaison, the lists of the mountings and of the standard parts still have to be filled in. Like what was just accomplished, the list of mountings is iteratively processed and each mounting between two custom designed parts is assigned to the relative liaison. As for standard parts, instead, the reorganized list is considered, which includes both single components and fastening sets. By going through the couplings, for each standard part all the custom designed parts in contact with it are stored, as well as for each fastening set the custom designed parts in contact with at least one of the composing parts. If the custom designed part identified are at least two, each possible pair of them is considered and if a liaison exists identified by one of these pairs of components, the standard part/fastening set is assigned to it.

These seem quite long operations since every item of the lists of couplings and mountings have to be analyzed. Although, all the needed information, such as the types of parts or the existence of contacts, is already computed and easily accessible as properties associated with each coupling/mounting. As a result, simple queries about the existence or not of an element in a list are performed, which do not require high computational costs and time.
At the end on the liaisons creation, it can happen that some standard parts remain not assigned to any liaison. The reasons are different and are discussed in the following, pointing out whether these are situations that can be solved by some reasoning on conventional representations and engineering knowledge, or issues that are not really easy to deal with:

- A standard part is excluded from liaisons when it is in contact with only one custom designed part. This situation is attributable to the issue of incomplete models or missing components. In fact, a typical example is the case of a fastener used to join a part of the assembly, with which is thus in contact, to an external component that instead is not represented in the analyzed model (Fig. 6a). This problem can not be overcome, in the sense that the standard part will remain out of the liaisons list, rather the information is stored and may be useful in next evaluations and tasks or it can be used as a warning of incompleteness of the model.
- A standard part or a fastening set is in contact with two custom designed parts and links them together, but these two components are not in contact with each other, i.e. no liaisons exist between them (Fig. 6b). This situation is fixed by creating a new virtual liaison between the two components, which is only equipped with the standard parts involved. It is clear that this will not be a real liaison in the sense of the definition given in Section 4.1, but it is significant to consider and save the connection generated by such standard parts.
- The standard part fastens two adjacent structural parts, but the contact between the fastening part and one of the two structural parts is not identified due to modeling errors, i.e. displacement of parts that generates clearances and intersections, or designer choices, e.g. not modeled holes (Fig. 6c). The second is an acceptable scenario, since in some cases the holes are not preformed into the parts when they are manufactured because they are generated by the insertion of fasteners, and therefore are not



(a) Not modeled custom designed part.

(b) Custom designed parts not in contact.

(c) Not modeled holes.

(d) Volumetric intersection.

Figure 6: Examples of standard parts not included in liaisons.

designed in the CAD models of the parts. To overcome the misleading situation, it is possible to evaluate the standard parts not included in liaisons and check if there are some intersection with other custom designed parts.

- The standard part is an O-ring and it is positioned between two custom designed parts in contact with each other, i.e. underlying a liaison. However, especially when the O-ring is modeled as a single toroidal surface, the contact between the standard part and one or both the custom designed parts is not detected because it is not a surface contact or it generates a volumetric intersection (see Fig. 6d). This issue can be solved by exploiting the information used in the standard parts recognition relative to the matching between standard parts and features. That is, the O-ring can be assigned to the liaison involving the two parts having the grooves recognized as seats of it.

In conclusion, the liaisons computation phase returns as final output the list L of liaisons along with a support list that indicates if some standard part has not been assigned to any liaison. In particular, the list L provides pairs of parts in contact equipped with properties aimed at enhancing their semantic understanding. The properties of each liaison are deduced from the analysis and processing of the data of the couplings associated, and are given as accessible data of the liaison.

5 GRAPHICAL USER INTERFACE FOR THE ENRICHED CAD MODEL INSPECTION

To allow designers and production experts to analyze the new assembly representation and the browsing of the provided data, a graphical user interface has been realized. It consists of a form where the CAD model is

shown and can be examined as in common CAD systems, sided by the original tree structure and a *Liaison assembly* form where the new organization of the assembly based on the liaison data structure is shown (forms 1 and 2 in Figure 7).
More in details, the enriched CAD model representation is presented as a new single-level tree, where each leaf is a liaison. By clicking on a liaison leaf, it is expanded and the composing parts and standard parts are listed below. In addition, the properties and the accessible data (e.g. couplings, mountings, contact information, etc.) are visualized on the right side of the same form and can be further selected to visualize their specifications (forms 3 and 4 in Figure 7). Also, the *Liaison assembly* form is linked with the visualization form in the sense that by clicking on an item of the liaisons tree (e.g. a liaison, a part, a standard part set, etc.) its corresponding components in the CAD model are highlighted.

5.1 Examples

Examples of visualization of the liaisons returned after the automatic processing of the CAD model of a fan assembly are presented in Figures 7 and 8. In the specific, the input model is made of 325 parts, 228 of which are recognized as standard parts. The total number of liaisons generated by the presented system, that completely describe the fan assembly, is 155, which is a very small amount compared to the pairs of parts in contact that would be detected if considering all the 325 parts at the same level, regardless of the standard parts. In the *Liaison assembly* interface the list of the 155 liaisons is visualized. In Figure 7 the first liaison is selected, which consists of the two parts P_1 and P_2, respectively colored green and yellow in the visualization window. It can be inferred that the liaison involves a single coupling, which is planar and the normal vector associated with the planar face of P_1 in contact with an opposite planar face of P_2 is parallel to the z axis. Figure 8, instead, shows the case where a liaison with standard parts is selected. More precisely, the liaison includes 24 copies of the same standard parts set consisting of screw, nut, and washer. To avoid redundant information, the liaison tree contains only a representative item indicating the standard parts sets composition, along with the number of its repetitions. All the sets are colored in the *Viewer* and their geometric attributes (e.g. centers and axes) are readable in the properties section.

In this way the CAD model of a complex assembly can be inspected through the browsing of its liaisons. The visualization of pairs of parts in contact, along with their contact information, is more significant in respect with the visualization of the single parts. Many details useful for the understanding of the components' relationship and their behavior within the assembly are in fact provided and highlighted. For instance, the aggregation of the standard parts in functional sets, as well as the grouping of the repetitions of the same standard part or standard part set emphasizes their role in connecting two custom designed parts. Such a visualization, along with the possibility to interact with the liaisons' elements, is intuitive and enhance the CAD model analysis.

In general, the automatic computation of liaisons and generation of the enriched CAD model have been tested on a set of about 20 industrial CAD models of different mechanical products, the number of parts of which varies from 35 to 490. The efficiency in the use of the new representation is evident especially in the cases of assemblies with the greatest number of components. As a matter of fact, most parts are actually standard parts (on average 40% of the total number of parts), and thus managing them as liaisons' properties, rather than parts underlying a liaison, allows to provide a limited number of items in the final liaisons list, as well as to enhance the semantics of contacts and their interpretation from the engineering standpoint.

6 CONCLUSIONS

In this paper a new data structure is defined that stands at the basis of an enriched CAD model representation. It is meant to integrate and provide product model and assembly process information in a unique object that

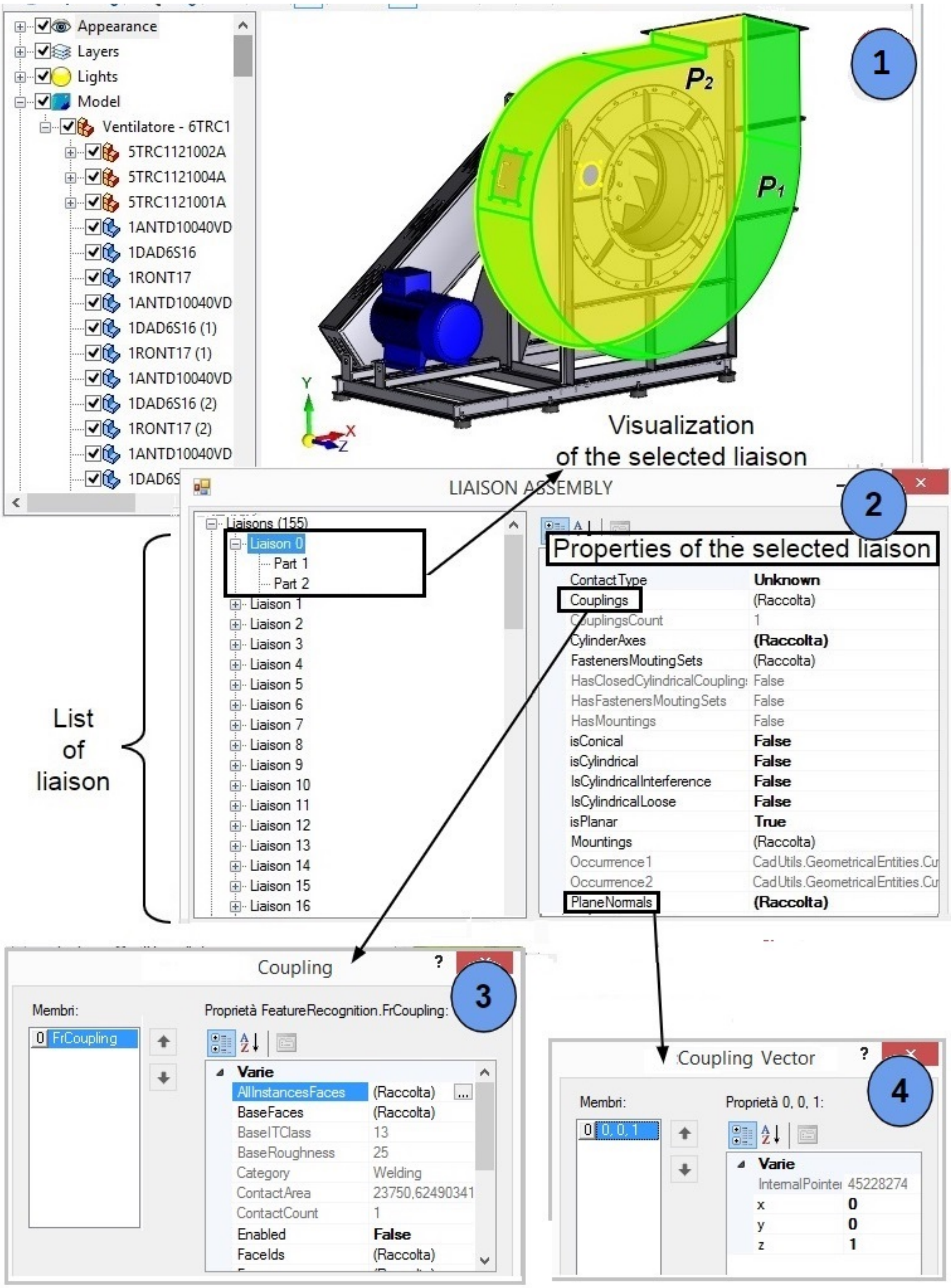


Figure 7: Interface developed for the visualization of the enriched liaison-based CAD model representation.

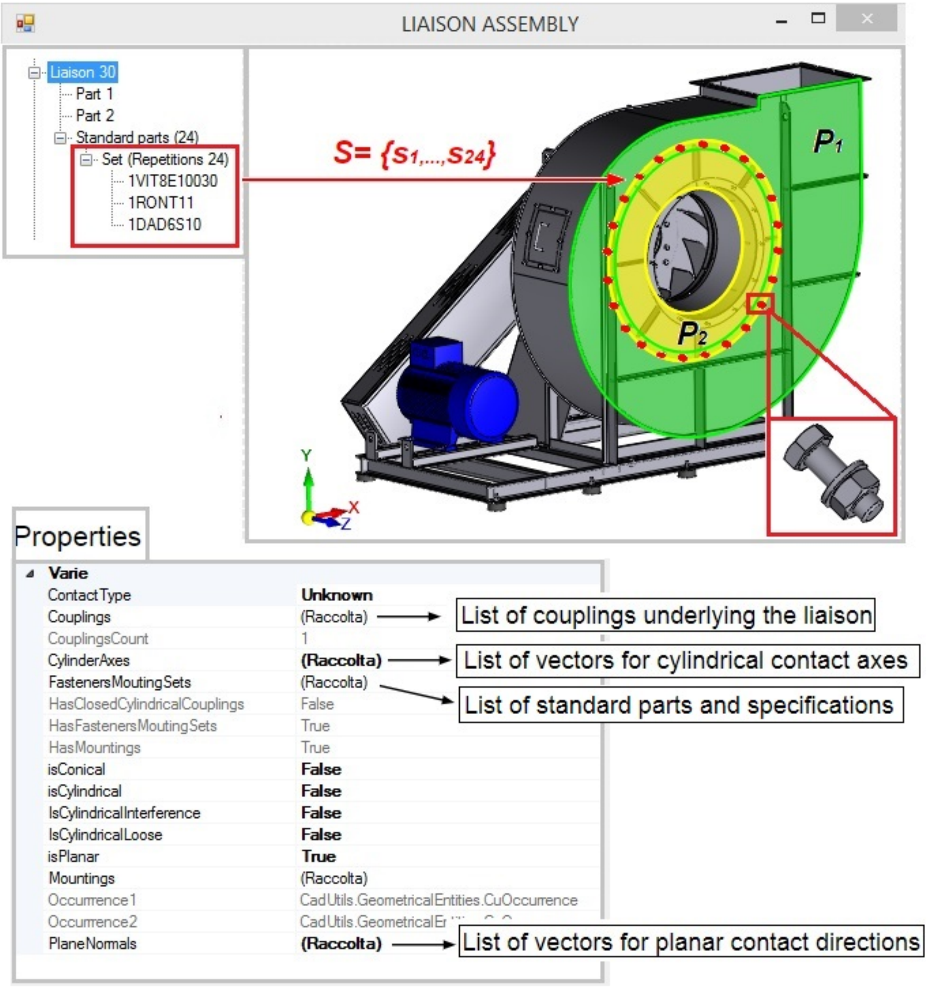


Figure 8: Example of visualization a liaison of the fan assembly having repeated standard parts set.

meets the requirements of completeness and ease of use. Respectively, completeness concerns the capability of combining in the same object both geometric data and high-level information. Ease of use refers to the availability of the semantic data, automatically extracted through a CAD model processing phase, in the new representation avoiding further computations and in the possibility to leverage them in a data exploitation phase by simple queries.

At this purpose, the potential and the benefits in using liaisons as starting point to address assembly tasks are demonstrated by the authors in different works. For instance, in [9] liaisons are exploited to identify engineering meaningful clusters, in [6] the semantic data results crucial to carry out a more realistic collision detection for the assembly sequence planning, while in [8] the liaisons and their properties result promising in the automation of the Design for Assembly analysis.

The use of liaisons, rather than the typical matrices or graphs in which nodes correspond to assembly components, to represent a mechanical assembly is advantageous under different aspects. On the one hand, liaisons allow to specify the assembly relations and organization gathering several data in a compact format. In fact, providing a list of pairs of parts, where standard parts are considered as attributes and grouped by type, allows to reduce the number of element to deal with but without loss of information. On the other hand, the new representation allows the understanding of the assembly process data and of the relations of the parts in an intuitive way thus facilitating optimization activities, such as the Design for Assembly analysis. It also makes possible to infer significant information implicitly contained in the CAD model (e.g. the attribute of mountings allows to infer fastening connections even if the fasteners are not modeled).

As regards future developments, the liaison data structure can be further improved, for instance, by defining liaisons not only between single parts, but even between subassemblies (e.g. bearings) in order to realistically treat subassemblies as single components and evaluate their behavior within the product as well as for parallel and human-robot collaborative assembling.

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