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Enhancing Product Semantics Understanding Through Automatic Part Type Recognition in CAD Assembly Models

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Abstract. Focus of this work is the recognition of the standard parts contained in a CAD assembly model, with the aim of enhancing the model semantics. Standard parts are components typically used in mechanical industry, which have a specific engineering meaning and follow international standards. In particular eight categories of standard parts are considered, i.e. screws, nuts, O-ring, washers, circlips,keys, studs and pins. The provided algorithm relies on the geometric and topological analysis of the CAD model parts. A part is assigned to one of the categories if it satisfies the geometric requirements extracted for that specific category, based on engineering knowledge and design rules. In addition, if a part is recognized as standard part, besides the class of membership, further information is provided as result, namely its engineering dimensions.

Keywords: CAD Model Processing, Type Recognition, Part Classification, Standard Part Detection, Assembly Semantics
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1 INTRODUCTION

Nowadays, to improve efficiency and reduce costs and the human workload, in mechanical industries, the product life cycle and, in particular, the manufacturing processes are deeply assisted in all their phases by the use of CAD assembly models. At this purpose, research is very active and several techniques have been defined and implemented to algorithmically address the most onerous and error prone tasks, from the assembly sequence planning to the subassembly sequence identification, from the assembly or parts retrieval for model and related knowledge reuse to the production and assembly costs estimation and optimization. In general, all these methods first implement a CAD model processing phase, where the features interesting for the specific process/analysis and their relations are recognized.

However, in most cases, the main weakness that can be observed is that all the data extracted basically rely on geometric information, while the intrinsic engineering meaning of the assembly's components is neglected

[16]. For example, the geometric type of the contact surfaces between two parts is taken into account, as well as their distance or their volumetric intersection, whereas the fact that the contact is strengthened by fasteners is overlooked. Even if knowing the type of the parts can be beneficial in selecting the most appropriate operations and sequences thus allowing more robust and efficient process definition, in CAD models all the component categories are treated at the same level. That is to say, there is no clear distinction between a screw or a sheet metal part, since they both are geometric objects only described as combination of bounding faces or their constructive elements (e.g. features and dimensional parameters) [4]. This because usually details associated with parts' functionalities and engineering meanings are implicit. This kind of data, in fact, may be included as annotations in the CAD model, but these attributes are not rigorous and unique since they depend on the designer choice, thus it may result difficult and time consuming to interpret them. Moreover, most of the time, especially when the CAD models are in standard exchange formats, such as STEP, the parts' meanings are lost, unless experts manually provide them [2].

We can conclude that the semantic interpretation of the CAD assembly model and its components is a very challenging but interesting topic, which deserves to be deeply investigated, since it can be exploited in several fields. To fill this gap, the paper proposes an automatic part type recognition methodology for the identification of some standard parts, largely employed in mechanical engineering. Making explicit the semantics of the components can be the basis for the understanding of the overall assembly semantics and functioning. The recognition relies on geometric analysis and engineering knowledge, avoiding experts' intervention for classifying and labelling parts. The main idea is to assign a part to a specific category (e.g. screw, nut, washer, etc.) when it complies with the engineering and design rules previously defined for that specific class of components.

The rest of the paper is organized as follow. In Section 2 a brief overview of the existing literature in the field of the CAD assembly model part classification and of the different methodologies adopted is outlined. Then, Section 3, after pointing out the standard part categories addressed in the classification, describes the approach implemented, together with the implemented algorithm structure. The geometric requirements, which stand at the basis of the recognition, are reported in Section 4 referring to each standard parts category. The validation of the approach and examples of its application to industrial CAD models are finally provided in Section 5.

2 STATE OF THE ART

The automated classification of three dimensional objects is a fundamental research subject highly addressed in the last decades [3]. It allows to label 3D parts by assigning them to well-known categories of parts, and then to improve their semantic meaning with additional information or even more to associate them with a precise functionality. The techniques used are different, especially according to the format of the analysed 3D objects, which can be represented by their surfaces as well as by their volumes. In general, three main categories of methods can be distinguished, namely: feature based methods, graph based methods and geometry based methods [10, 18]. 3D objects classification can find application in several fields, such as medicine, architecture or cultural heritage, but this work focuses the attention on the recognition of parts of mechanical assemblies.

Two are the main reasons according to which parts recognition and classification gained interest in industrial mechanical engineering. On the one hand, increasingly larger database of 3D models of components or assemblies are becoming available and it results very challenging to easily manage them and manually find target parts [13]. As a consequence, automatic parts classification, retrieval and clustering tools have been studied and developed, in order to assist designer in the different product manufacturing phases, from the modeling to the reuse tasks (e.g. [5, 7, 9]). On the other hand, a real mechanical product is made of many parts of various shapes and sizes and with different usages, but CAD assembly models rarely include high-level parts specifications, such as their functionalities, and it is very limiting. Cataloguing CAD model parts by assigning them to engineering components classes would thus enhance the semantic value and the understanding of the entire assembly, without the need of experts intervention.

In this regard, in mechanical engineering there exists a set of parts, that is to say the standard parts, that have a precise role in the assembly, and thus a more easily recognizable semantic value, moreover they have almost recurrent shape, possibly respecting standardised rules. Thanks to these characteristics, standard parts deserve to be recognized and classified, because the knowledge of them would facilitate the product development process and improve the CAD model processing algorithms, for example reducing the number of parts to deal with, allowing the identification of elements to be ignored or treated in predefined manners (e.g. [1]).

In literature several researches about assembly's parts classification and standard parts semantic values exploitation can be found. Classification approaches, according to the strategy adopted, can be divided in procedural and artificial intelligence methods. The former exploit geometric and shape information and, when available, parts' arrangement in the assembly and their contacts. Some of them are more targeted at the identification of single specific components, possibly exploiting different shape descriptors [8], or at the recognition of a restricted number of entities, to derive structural information about the assemblies [17]. Others aim to classify parts according to kinematic as well as functional properties [15, 19]. The more recent artificial intelligence methods, instead, allow the identification of a large portion of mechanical parts thanks to machine learning [6, 11, 14] or deep learning [12] techniques. These tools, however, in general are time consuming in the training phase, to let the algorithms learn, and require massive data sets of good quality, to achieve considerable accuracy.

This paper describes a practical standard parts recognition and classification approach, validated through its implementation within a commercial system for product cost evaluation. In particular, it is proposed not only to assign the parts to a category, but also to characterise them by the main engineering dimensions (e.g. length, width, thread, etc.) and deduce their semantic meaning. Aiming to provide an automatic part classification, avoiding a great computational effort, but at the same time ensuring reliable results, the approach is based on geometric analysis and engineering knowledge on the class characteristics and usage. It is in fact evident that, from an engineering point of view, standard parts' shapes are ruled by regulations. That is to say, excluding additional customization, each element belonging to a class is characterized by common class-specific features and its design follows international standards. Just think to the class of screws: although several types of screws exist, all of them always have a head and a stem, and the relationship between their lengths has to be in a given range. For each part category, catalogues exist detailing the general rules they have to follow and the admissible sizes.

Thus, exploiting engineering knowledge on the class characteristics, CAD model geometric analysis and feature recognition algorithms, the proposed method analyses each assembly's part and assesses if its geometry respects a specific class distinguishing characteristics both in shape and sizes.

3 STANDARD PART TYPES RECOGNITION

Real mechanical assemblies are made of many different parts. At first glance, a rough distinction can be made between custom designed and standard parts. Custom designed parts generally constitute the body of the assembly (e.g. sheet metal, beams, plates, pipes, etc.) and they can be specifically created for the product under development, without complying with international norms. The standard components, instead, have a more precise role in the assembly, a more easily recognizable semantic value, and moreover they meet international standard in shape and dimensions (usually associated with codes such as UNI, DIN, ISO, etc.). On the one hand standard parts serve to join the custom designed components (i.e. fasteners), on the other hand they are parts with an intrinsic and well known functionality (i.e. gears, bearings). Actually standard parts are categorised according to their role within the assemblies, consequently the awareness of them is crucial for engineers. However, the knowledge of standard parts is not given in CAD assembly models in STEP format.

Starting from the above assumptions, the final aim of this research is the creation of a tool which takes in

input a CAD assembly model in STEP format and returns the list of all the standard parts contained therein. The core and the novelty of this application is in the standard parts' types recognition algorithm, which is based on the specification of standard engineering and design rules in terms of shape and geometric features of the parts.
In this section, first, the recognized categories of standard parts are pointed out, then an overview of the approach developed is provided, together with the key points of the algorithm.

3.1 Standard Parts Categories

In the practical manufacturing industry there is plenty of category of standard parts, and related subcategories, catalogued in engineering manuals and, furthermore, available on online libraries, to be exploited in the modeling of products CAD assembly. However, it is evident that, on the one hand, the use of one type of standard parts rather than another depends on the product class and on the materials of the parts involved: on the other hand, some standard parts are used in very targeted cases. Consequently, a comprehensive classification and recognition of all the existing standard parts is indeed demanding and, at the same time, little usable at an industrial level, compared to the workload it would require.

Since this research is carried out in partnership with the Italian engineering software development company Hyperlean, which mainly deals with industrial CAD models of mechanical components of automatic machines, the proposed classification is focused on the recognition of the standard parts largely employed in this type of products.
The standard parts categories currently considered are therefore eight: screws, nuts, O-ring, washers, circlips, keys, studs and pins. Some of these classes, i.e. O-ring, washers, keys and studs, refer to a single type of parts, while the others, i.e. screws, nuts, circlips and pins, include a large variety of parts, which differ in features and usages. As a consequence, in the latter case, it is necessary to distinguish subcategories, in order to return more accurate results. In particular, as better explained in Section 4.1, screws are divided in eight subcategories depending on the head shape, that are: *hex head screws*, *socket hex head screws*, *socket hex countersunk head cap screws*, *cross recess countersunk flat head screws*, *cross recess countersunk raised head screws*, *cross recess raised cheese head screws*, *slotted pan countersunk head cap screws*, *slotted flat countersunk head cap screws*. Nuts include two subcategories, that are *standard nuts* and *cap nuts*, according to whether they have a through hole or a non-through hole closed on one side by a domed end. Circlips consist of five subcategories according to the ring ends behaviour and the internal shape, namely: *internal circlips*, *external circlips*, *snap rings*, *rings type G* and *rings type E*. Pins, then, are divided into two subcategories which are *not holed pins* and *holed pins*. The categories, and the associated subcategories, are summarized in Table 1.

It is to underline that the eight categories considered are referred to standard parts made of a single component, that is to say standard parts modeled as assemblies are not considered (e.g. bearings). Moreover, another peculiarity common to all categories is that they follow international standards for shape and dimensions, and, as we are going to explain, this is a fundamental assumption for the correct functioning of the algorithm.

3.2 Recognition Approach

The proposed recognition algorithm applies a rule based approach which mainly exploits geometric and topological information present in the Boundary Representation (B-rep) of the model as filters for discarding/accepting a part class membership. As a consequence, it is fast in providing the resulting classification. Moreover, it can be integrated in several contexts as preliminary phase to assist the CAD model processing.

Gathering up engineering knowledge of mechanical components, catalogues on standards and design rules, for each of the eight considered categories, the most typifying aspects have been singled out. That is to say,

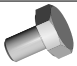
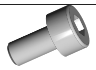
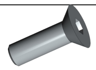
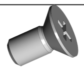
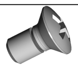
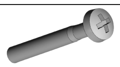
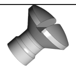
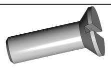
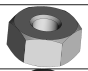
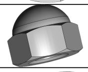
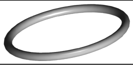
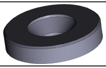
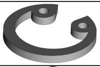
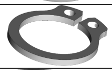
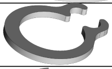
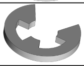
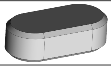
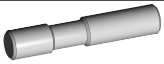
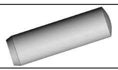
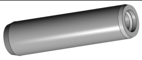
Category	Subcategory	Image	Dimensions and geometric properties
Screws	Hex head		Nominal Diameter, Length, Head Height, Key Size, Center and Axis
	Socket hex head		Nominal Diameter, Length, Head Height, Key Size, Socket Depth, Center and Axis
	Socket hex countersunk head cap		Nominal Diameter, Length, Head Height, Key Size, Socket Depth, Center and Axis
	Cross recess countersunk flat head		Nominal Diameter, Length, Head Diameter, Groove Width, Cross Depth, Center and Axis
	Cross recess countersunk raised head		Nominal Diameter, Length, Head Height, Head Diameter, Groove Width, Cross Depth, Center and Axis
	Cross recess raised cheese head		Nominal Diameter, Length, Head Height, Head Diameter, Groove Width, Cross Depth, Center and Axis
	Slotted pan countersunk head cap		Nominal Diameter, Length, Head Height, Head Diameter, Slot Depth, Center and Axis
	Slotted flat countersunk head cap		Nominal Diameter, Length, Head Diameter, Slot Depth, Center and Axis
Nuts	Standard		Nominal Diameter, Head Height, Key Size, Center and Axis
	Cap		Nominal Diameter, Head Height, Key Size, Center and Axis
O-ring	-		Diameter, Chord, Center and Axis
Washers	-		Thickness, Inner Diameter, Outer Diameter, Center and Axis
Circlips	Internal		Internal Diameter, External Diameter, Thickness, Center and Axis
	External		Internal Diameter, External Diameter, Thickness, Center and Axis
	Snap ring		Internal Diameter, External Diameter, Thickness, Center and Axis
	Ring type G		Internal Diameter, External Diameter, Thickness, Center and Axis
	Ring type E		Internal Diameter, External Diameter, Thickness, Center and Axis
Keys	-		Height, Length and Width
Studs	-		Nominal Diameter, Length, Threads Length, Center and Axis
Pins	Not holed		Length, Diameter, Center and Axis
	Holed		Length, Diameter, Hole Nominal Diameter, Center and Axis

Table 1: Summary table of the standard parts categories considered and the associated extracted dimensions.

we have identified those characteristics, both relative to shape and sizes, that a component must necessarily have to belong to one of the categories. Moreover, standard parts from multiple online platforms (e.g. https://b2b.partcommunity.com, https://www.3dcontentcentral.com/, etc.) are analyzed, to ensure that different CAD modeling approaches are addressed. The properties are then translated in geometric requirements, such as the presence of specific types of faces (e.g. planar, cylindrical, toroidal, etc.), their particular arrangements, ranges for some the dimensions. It is to underline that the proposed approach is not restrictive. The evaluation criteria are conceived to include the minimum needed characteristics, in order to allow the recognition of both parts modeled in different ways and varieties of parts. For example, whether the chamfers are modeled or not is not discriminatory, as well as the absolute sizes of the parts are not considered due to their variability, but rather the ratio of the sizes is taken into account.
Moreover, thanks to its structure, the algorithm can deduce additional information beyond the simple category, and associate them with the components. From the design point of view, the center and the axis of the CAD model of the part, when it makes sense, are computed and stored. This data is of particular interest in assembly/disassembly planning tasks, since for example it can suggest assembly/disassembly preferential directions. From the engineering point of view, instead, the dimensions generally used in mechanics, and reported in catalogues, are automatically extracted, such as length, width, height, diameter, nominal diameter, socket depth, key size or chord. In this way, parts of the same class can be then grouped by dimensions, as it is relevant in several tasks such as costs estimation. Practical information is thus supplied with no human intervention, and it enhances our classification, since dimensions are rarely automatically returned by existing methods.

3.3 Recognition Algorithm

From the development point of view, the recognition algorithm is structured as elimination filtering process. That is to say, given a CAD model part, its possible membership to one of the standard parts categories is investigated. If the analysed part meets all the geometric requirements for a certain category, then no further verification is needed. The part is associated with that category and dimensions are extracted. If, instead, the part does not satisfy the requirements for any of the categories, consequently it will not be classified as a standard part.

The investigation on part membership to the each of the eight categories is carried out through eight functions which return the Boolean value true if part belongs to the specific category. The functions are independent from one another, and follow a schema that, proceeding by steps, iteratively analyses the geometric requirements the part have to satisfy to belong to the given category. Once the part characteristics do not satisfy a requirement, the function returns false, without evaluating the succeeding features. To minimize the number of operations as much as possible, the order in which the geometric requirements are evaluated is meant to first ensure the part meets the fundamental and most representative features of the category, and then evaluate the properties associated with more specific details and with the distinction in the different subcategories. In general, first, the faces are counted: if the number of faces is in a given range, the algorithm proceeds to verify the type of surfaces of the faces and to evaluate their relative positions (e.g. parallel, perpendicular, etc.), the symmetry of the part and the existence of specific sequences of faces. If combination specified for the considered categories is satisfied, the component is supposed to belong to the corresponding class. To confirm this assumption, the dimensions and their ratio are checked.

3.4 Preliminary Phase

As the final tool takes an assembly as input, all the CAD model parts are analysed individually, and the recognition algorithm explained in Section 3.3 is applied singularly on each of them.

However, it has to be said that right after the import of the CAD assembly model in STEP format, all

the parts are subject to a preliminary phase of normalization of their geometry. In fact, STEP describes components' geometric models in a B-Rep format, but the representation is not unique. Thus, two STEP files may refer to the same object, but involving different geometrical entities. In particular, an edge can be defined as a set of topologically connected smaller edges laying on the same curve, rather than a single curve. The same applies to faces, where a face can be divided into smaller ones that share the same surfaces and are topologically connected. For example, a cylindrical surface can be represented either with two half cylinders or a single cylindrical patch.
Define a unique representation of edges and surfaces is crucial to obtain a set of geometric entities that is consistent with the geometric requirements used in the recognition algorithm, in order to reduce the number of admissible possibilities to take into account. To this aim, first the geometric formulation of each surface, which can vary according to designers' choice and adopted tools, is converted to the more common and meaningful formulation, that is to say plane, cylinder, cone or torus. For example, a surface of revolution with a line as generator is converted to a cylinder/cone, or a first-degree NURBS is converted to a plane. The same geometry cast is also applied to the curves. Then, adjacent faces that belong to the same canonical surface are merged into one entity: a maximal face. Edges are also grouped into maximal edges using the same criterion. As a result, if the geometric conditions require that a part must have a hole to belong to a certain category, the algorithm has to simply search for a closed cylindrical face which is necessarily described by two closed edges without vertices. Without face and edge normalization,, the algorithm should verify the connection between all the opened cylindrical faces, and any resulting closure.

4 GEOMETRIC REQUIREMENTS

In this section, the distinctive engineering features identified for each standard parts category are briefly highlighted. For some of the categories, the deriving geometric and topological requirements for CAD model parts, combined with the standard rules usually followed by designers, are then listed. The lists' items and their order correspond to the steps implemented in the boolean functions to investigate a part membership to a category.

4.1 Screws

Screws are among the widespread threaded fasteners used in mechanical engineering to link two or more parts. The most characterising aspect of a screw is the presence of a head on one end. The head is usually larger than the body of the screw and its functionality is to provide a conveying surface and to keep the screw from being driven deeper within the fixing parts during the mounting. A screw's head can be of different types. On the one hand, heads differ in shape: for example, they can be hexagonal, cylindrical or conical, with flat or rounded top. On the other hand they can have several drive designs: the most general drives are the hex socket, the crossed and the slotted. Depending on the combination of head and drive shapes, the different type of screws are defined. In particular, in the proposed classification, eight subcategories of screws are taken into account:

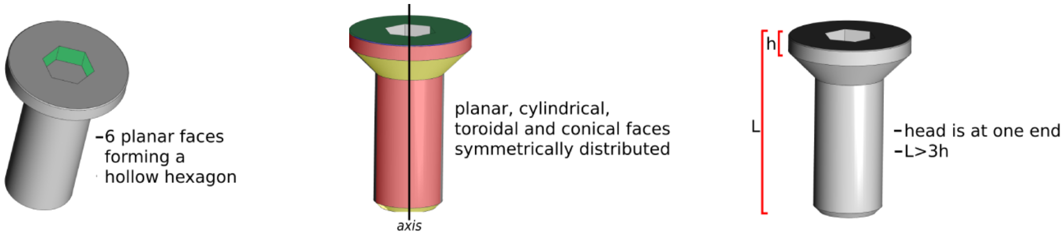
- hex head screws: with hexagonal head;
- socket hex head screws: with cylindrical head and hex socket as drive;
- socket hex countersunk head cap screws: with conical head and hex socket drive;
- cross recess countersunk flat head screws: with conical head, flat top and crossed drive;
- cross recess countersunk raised head screws: with conical head, rounded top and crossed drive;
- cross recess raised cheese head screws: with cylindrical head, flat top and crossed drive;
- slotted pan countersunk head cap screws: with conical head, rounded top and slotted drive;

- slotted flat countersunk head cap screws: with conical head, flat top and slotted drive.

The remaining portion of a screw, from the underside of the head to the tip, is then known as shank and it is cylindrical-like. The shank may be fully threaded or partially threaded; the distance between each thread is called pitch, while the major diameter of threads is called nominal diameter. It is to underline that it is a common design strategy not to model threads, but rather to represent them as smooth cylindrical surfaces with diameter the nominal diameter. Finally, there exist international standards that define the admissible relations between a screw head height, shank length, diameter and pitch.

These engineering features, typical of almost all screws classes, have been translated in geometric requirements. For simplicity of the implementation, the function of the membership of a part to the screws category includes three separate functions depending on whether the screw is hexagonal/socket hex, crossed or slotted. Here the geometric requirements a CAD model part should satisfy to be classified as a hexagonal screw (socket or not) are reported.

1. The number N of faces of the part is in the range $10 < N < 40$.
2. There must be a set of 6 planar faces forming a regular polygon, i.e. the hexagonal head, which can be both hollow and not hollow. If the hexagon is not hollow, it will be the head of the screw, if instead the hexagon is hollow, it will be the socket drive. The height of the polygon will be the height of the head of the screw (Fig. 1a).
3. The remaining faces of the part, which can be of any type (planar, cylindrical, toroidal or conical), must be symmetrically distributed, and with normal vector/axis coaxial with the axis of the head and with each other, i.e. the screw is axisymmetric. The common axis will be the axis of the screw (Fig. 1b).
4. By ordering the faces along the axis according to their position, the head's faces must be at one end and not in middle position. The distance between the first and the latter faces will be the length of the screw. The nominal diameter will be the major diameter among those of the cylindrical faces (Fig. 1c).
5. As for admissible dimensions, the screw length must be at least three times the height of the head (Fig. 1c).



(a) Requirement 2. (b) Requirement 3. (c) Requirements 4. and 5.

Figure 1: Examples of a part that meets the requirements to belong to hexagonal screws category.

For crossed and slotted screw recognition the steps addressed are similar. The main difference is in point 2, where planar faces, instead forming a polygon, have to form respectively a cross and a slot.

4.2 Hex Nuts

Nuts are threaded fasteners almost always used combined with screws, in order to lock screws and avoid them to raise out of the holes. The most common nuts are the hexagonal ones,in which are also included the hexagonal cap nuts. They have a very simple form, since they are hexagonal rings with a cylindrical threaded hole, which can be a through hole or a non-through hole closed on one side by a domed end. As a consequence, the geometric requirements a part has to meet to belong to hex nuts category are very simple, that is to say:

1. The number of faces N is in the range $9 < N < 35$
2. There must be a set of 6 planar faces forming a regular polygon, i.e. the hexagonal external surface, which must be not hollow. The height of the polygon will be the height of the nut.
3. The remaining faces of the part, which can be of any type (planar, cylindrical, spherical, toroidal or conical), must be symmetrically positioned coaxial with the hexagon and with each other, i.e. the nut is axisymmetric. The common axis will be the axis of the nut.
4. There must be a cylindrical hollow face, i.e. the hole. The diameter of the cylindrical face will be the nominal diameter of the nut.
5. Let the total nut length be the dimension of the bounding box of the part along the axis. The length must be at most three times the height of the hexagonal portion of the parts.

4.3 O-ring

O-ring is a deformable component designed to be placed in a groove and compressed during assembly between two or more parts, creating a seal at the interface. O-ring is recognizable thanks to its toroidal shape, and can be of different sizes, both in diameter and cross section. The geometric requirements and common design rules for CAD model of O-ring are thus the following:

1. The number of faces N is in the range $1 \leq N < 8$.
2. Among all the faces, there must be at least a not hollow toroidal face.
3. The other faces must be cylindrical, not hollow toroidal, or ring-shaped planar, and must all be coaxial with each other. Furthermore, all the part's edges must be arcs of a circle.

The average of the toroidal faces' diameters will be the diameter of the O-ring, while the average of the toroidal faces' cords will be the cross section.

4.4 Washers

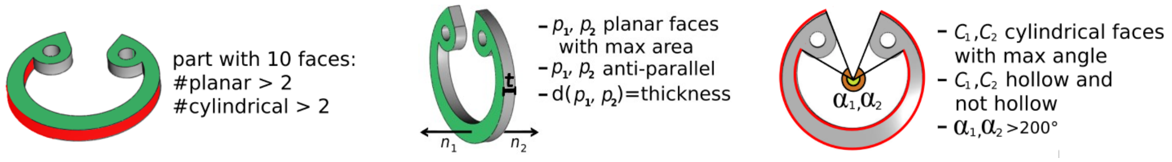
Washers are fasteners used combined with screws and nuts, to distribute their load or with spacer functionality. Washer are ring-shaped, made of a thin plate with a central hole and can have both smoothed and not smoothed edges. Even though international standards define the admissible ratio between the hole diameter and the thickness of the washer, these components have a little detailed geometry and consequently it is challenging to provide a correct classification. The knowledge of the contact with a screw or a nut would be very helpful to ensure a ring-shaped part is a washer, and thus it will be part of future works.

4.5 Circlips

Circlips are deformable fasteners largely exploited in mechanic to hold components or assemblies onto a shaft or in a bore, in particular their function is to avoid lateral movements but allow rotations. The simplest circlips are open rings with planar faces, defined as snap rings. More particular types of circlip, namely the internal and the external circlips and rings of type G, instead, have ears or lugs at the ends which can be holed or not. Finally, also the rings of type E are commonly used as fasteners, and they are internally carved too. To

ease the function of the membership of a part to the circlips category, we have distinguished the identification of rings of type E from that of the other subcategories, since the geometric and topological requirements are quite different.
As a consequence, the criteria according to which a part in CAD model can be classified as an internal circlip, external circlip, snap ring or ring of type G are:

1. The number of faces N is in the range $6 < N < 30$ (Fig. 2a).
2. There must be at least two planar faces, i.e. the top and the bottom surfaces, and two opened cylindrical faces, i.e. the internal and external surfaces (Fig. 2a).
3. Among the planar faces, let p_1 and p_2 be the two planar faces with biggest area. The faces p_1 and p_2 must be anti-parallel and their bounding box must be equal to the bounding box of the entire part. The distance $d(p_1,\ p_2)$ between the two planar faces will be the thickness of the circlip (Fig. 2b).
4. Among the opened cylindrical faces, let c_1 and c_2 be the two with maximum angles, α_1 and α_2. The faces c_1 and c_2 must be one hollow and one not hollow, coaxial with each other, and with axis parallel to the normal vectors of the planar faces p_1 and p_2. The angles α_1 and α_2 must be in the range $200° < \alpha_1, \alpha_2 < 360°$. The not hollow face's diameter must be bigger than the one of the hollow face. The hollow and the not hollow faces will be respectively the internal and the external faces of the circlip, thus their diameters will be the internal and external diameter of the circlip (Fig. 2c).
5. If there are closed cylindrical faces, they must be 2, i.e. the holes. Let h_1 and h_2 be the two closed cylindrical faces, h_1 and h_2 must have equal diameters, minor than the internal diameter of the circlip.



(a) Requirements 1. and 2.   (b) Requirement 3.   (c) Requirement 4.

Figure 2: Examples of a part that meets the requirements to belong to circlips category.

If requirement 1 to 5 are satisfied, the analysed part is recognized as a circlip. To distinguish between the different categories, the following verification is made. When the holes are recognized, if the internal face has bigger angle then the external face the part is assigned to the external circlips category, otherwise it is assigned to the internal circlips (Fig. 3). When no holes are identified, and there are no other opened cylindrical faces except those already considered, the part is classified as snap ring; on the contrary, if there are other pairs of equal and opposite opened cylindrical faces, the parts is a ring of type G.

Finally, the requirement for a part to belong to rings of type E are:

1. The number of faces N is in the range $8 < N < 30$.
2. There must be at least two planar faces, i.e. the top and the bottom surfaces, and three opened cylindrical faces, i.e. the internal and external surfaces. There must not be closed cylindrical faces.
3. Among the planar faces, let p_1 and p_2 be the two planar faces with biggest area. The faces p_1 and p_2 must be anti-parallel and their bounding box must be equal to the bounding box of the entire part. The distance between $d(p_1,\ p_2)$ between the two planar faces will be the thickness of the circlip.

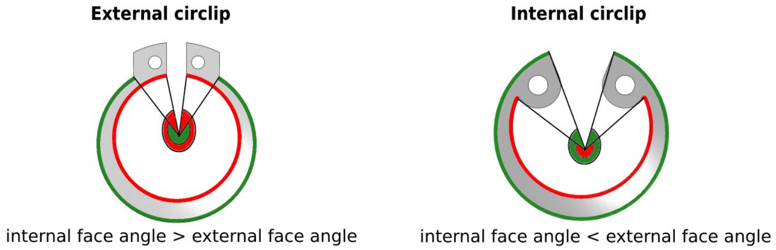


Figure 3: Distinction between external and internal circlips.

4. Among the opened cylindrical faces, let c be the face with maximum angle, α. The face c must be not hollow, with axis parallel to the normal vectors of the planar faces p_1 and p_2. The angles α must be in the range $200° < \alpha < 360°$. The face will be the external face of the circlip, thus its diameters will be the external diameter of the circlip.

5. The remaining opened cylindrical hollow faces are grouped in sets if belonging to the same circumference, i.e. if they have same radius, center and axis. At least one set of faces belonging to the same circumference must be found. Let S be the set, including at least two faces, associated with the circumference with minor diameter and coaxial with the external face of the circlip. The diameter of the circumference will be the internal diameter of the circlip (Fig. 4).

6. The internal diameter must be minor than the external diameter.

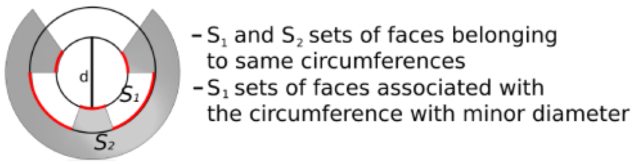


Figure 4: Example of part that meets the requirement 5. for rings of type E.

4.6 Keys

Very common elements, normally present in machines with power transmission shafts, are the keys. They are standardised parts, used to connect a rotating element to a shaft with the function of avoiding the relative rotation between the two parts. Keys are very simple components with the shape of a rectangular parallelepiped. Some, or even all, of the edges can be chamfered; the two lateral end faces can be cylindrical like or not. The proposed algorithm considers only the keys with cylindrical faces, since the others have too general geometric characteristic and may lead to an excess of false positives. Therefore, the geometric requirements taken into account are:

1. The number of faces N is in the range $6 < N < 20$.

2. There must be at least four planar faces, i.e. the lateral faces, and two opened cylindrical faces, i.e. the end faces.

3. Let c_1 and c_2 be the two opened cylindrical faces. They must be not hollow, with parallel axes, and same area. The major distance between c_1 and c_2 will be the length of the key.

4. Let $P_b = \{p_1, p_2\}$ and $P_l = \{p_3, p_4\}$ be two pairs of faces such that p_1, p_2, p_3 and p_4 are the four planar faces with biggest area. P_b and P_l must be formed by two anti-parallel planar faces with same area, in particular $A(p_1) = A(p_2) < A(p_3) = A(p_4)$. P_b and P_l must be perpendicular with each other, and the faces of P_b must have normal vectors parallel to the axes of the cylindrical faces. The distance between p_1 and p_2 will be the height of the key, while the distance between p_3 and p_4 will be its width.

In future, to enhance the recognition of keys, the adjacent parts should be considered. In fact, from the mounting point of view, keys follow very precise standards: both the shaft and the other part that are connected by a key, present a recess, namely a keyway, along the axial direction, where the key is inserted to lock the components. The identification of a parallelepiped-shaped part in contact with two axisymmetric part having keyways would immediately suggest the first element is a key.

4.7 Studs

Studs are fasteners characterized by a very simple shape: they are cylindrical parts threaded on both ends, or even along their complete length. Since threads are not explicitly designed in CAD models, but they are simply represented as cylindrical surfaces with diameter the nominal diameter, fully threaded studs appear as simple cylinder and are therefore too general to be classified based on mere geometric requirements, and can be confused with pins. As a consequence, the proposed recognition is focused on the not completely threaded studs, with equal or unequal threads length at the ends. The associated CAD models, in fact, is characterized by three coaxial cylinders, where the two at the ends have same diameter, corresponding to the nominal diameter, which is bigger than the central one (see Tab. 2).

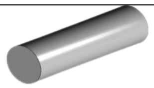
	Real	CAD Model
Fully threaded stud		
Two ends threaded stud		

Table 2: Examples of fully threaded and two ends threaded studs and relative CAD models.

4.8 Pins

Pins are not threaded mechanical fasteners, which are designed to be inserted through preformed holes. They have the function to hold together parts of an assembly by interference fit. As for the shape, the most common pins, are basically cylindrical parts. They can vary at the ends: the end faces can be flat or rounded, and their edges can be both, or simply one, chamfered (with same or different chamfers). Moreover, pins can have a threaded hole in one end, so that a screw can be inserted to help remove the pin from a blind hole. Thus, in the classification we will distinguish between not holed and holed pins.

5 EVALUATION AND APPLICATION EXAMPLE

This section aims to validate the methodology we have discussed and to provide examples of its application on real industrial CAD models.

Since the research is part of a project carried out in partnership with the Italian company Hyperlean (https://hyperlean.eu), the proposed algorithm is implemented as a module of their industrial software LeanCOST, developed using C++, C#and VB.NET. languages.

5.1 Recognition Validation

The part type recognition approach has been first validated on a test-set of 180 standard parts belonging to the eight categories.The test-set is shared at the page http://partrecognitiondataset.ge.imati.cnr.it. The parts are divided among the different classes as shown in Table 3 .

The different number of parts evaluated for each category is justified by the difference of the complexity and variability of the classes. The more subcategories, the more test-cases are needed. It is evident, for example, that screws recognition has to be tested on a bigger number of components to adequately address the eight different subcategories classification. Moreover, there can be a high variability among the components of the same category, which depends on how designers model the parts, because they often use simplifications or do not meet dimensional standards. To cover as much scenarios as possible, parts modeled at different levels of details (e.g. with/without chamfers or fillets) are taken into account, as well as parts with different dimensions.

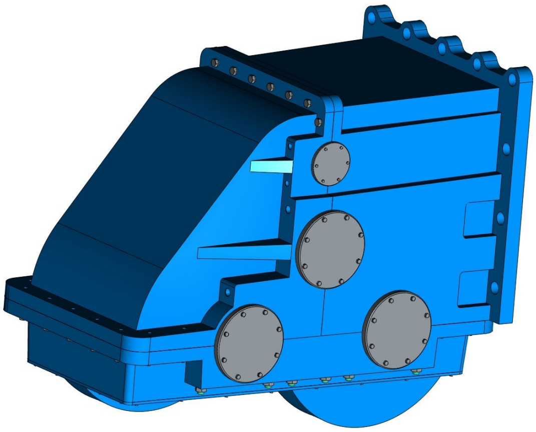
Category	**Parts**	**Parts recognized (%)**
Screws	60	80%
Nuts	20	90%
O-ring	10	90%
Washers	10	70%
Circlips	30	80%
Keys	10	80%
Studs	20	35%
Pins	20	80%
TOT	180	75%

Table 3: Parts used in the type recognition validation divided by categories.

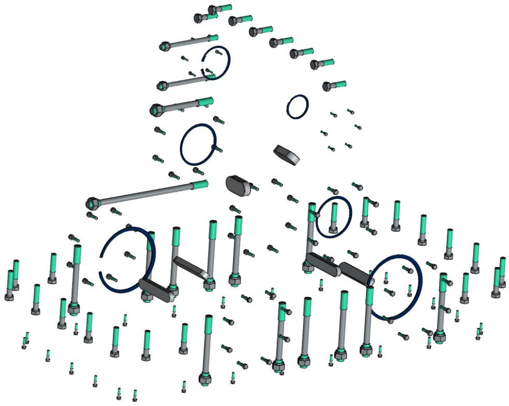
Results show that the provided method is able to correctly recognize the class of membership of most of the components given in input. The major issue is, however, in the studs identification. Due to their simple shape, studs can be easily mistaken for not holed pins. Both studs and pins, in fact, are cylindrical components. Actually, the main difference is that the first is threaded while the latter is not. As a consequence, since threads are not explicitly represented in the STEP, the geometric requirements for studs and pins are very similar. As far as the other categories is concerned, they are not confused with each other. Rather, when the recognition fails, it is because some geometric requirements are not met, especially those deriving from the admissible dimensions check, or some modeling errors occur. More in details, for example, some screws are not recognized because the shank is too short, other because the crossed drive is modeled in a not standard way (e.g. the cross is not composed of pairs of anti-parallel faces). As for washers, the recognition fails when the hole diameter is too small, and then the ratio between inner and outer diameters is out of the defined range. Circlips, instead, are usually not recognized due to modeling errors, such as the fact that one or both the cylindrical faces have too small angle.

5.2 Recognition Application

The use of the developed tool for identifying the standard parts present in an industrial CAD model of a gearbox is now presented.



(a) CAD model of a gearbox.



(b) Parts recognized by the algorithm.

Figure 5: Examples of a part type recognition applied to an industrial CAD model of a gearbox.

The gearbox CAD model (Fig. 5a) is made of 426 parts, a reasonably high number, that consequently involves computational effort during the model analysis and processing phase, as well as in several assembly tasks (e.g. assembly sequence planning, subassembly identification, etc.). At this purpose, the classification can significantly improve the assembly's details available and reduce the number of parts to analyse, by recognizing and labelling most of the standard parts included in the model, and thus enhancing the semantic and engineering knowledge of the assembly.

The parts classified are in fact 282 (see Fig. 5b), the 66% of the total, and more specifically: 112 hex head screws (divided in 5 subgroups by thread pitch and length), 86 washers (divided in 3 subgroups by diameter and thickness), 4 internal circlips ((divided in 3 subgroups by diameter and thickness), 42 snap rings (divided in 3 subgroups by diameter and thickness), 16 nuts (divided in 2 subgroups by thread pitch and height), 16 studs (divided in 3 subgroups by thread pitch and length) and 6 keyways (divided in 3 subgroups by length, width and height).

In Fig. 6 an example of how the developed tool displays the classification results is presented. In the *STANDARD PARTS* form, all the subcategories of standard parts identified are itemized and divided according to the different subgroups listed above. By clicking on one item the associated components are highlighted in the CAD model. In this way a general overview of their arrangement is also given, which can be very useful. Finally the extracted engineering dimensions are provided on the right side of the same form.

From these results it is evident that more than half of the assembly's components are actually fasteners or, however, parts with a precise engineering meaning. The method presented allows to automatically recognize them in few seconds, only starting from the CAD assembly model. The classification of the parts can therefore be exploited in different ways, for example to simplify the graph of the assembly's parts contacts, excluding standard parts from the nodes of the graph, but rather leveraging the knowledge of their functionality as contact attributes, reducing the computational cost.

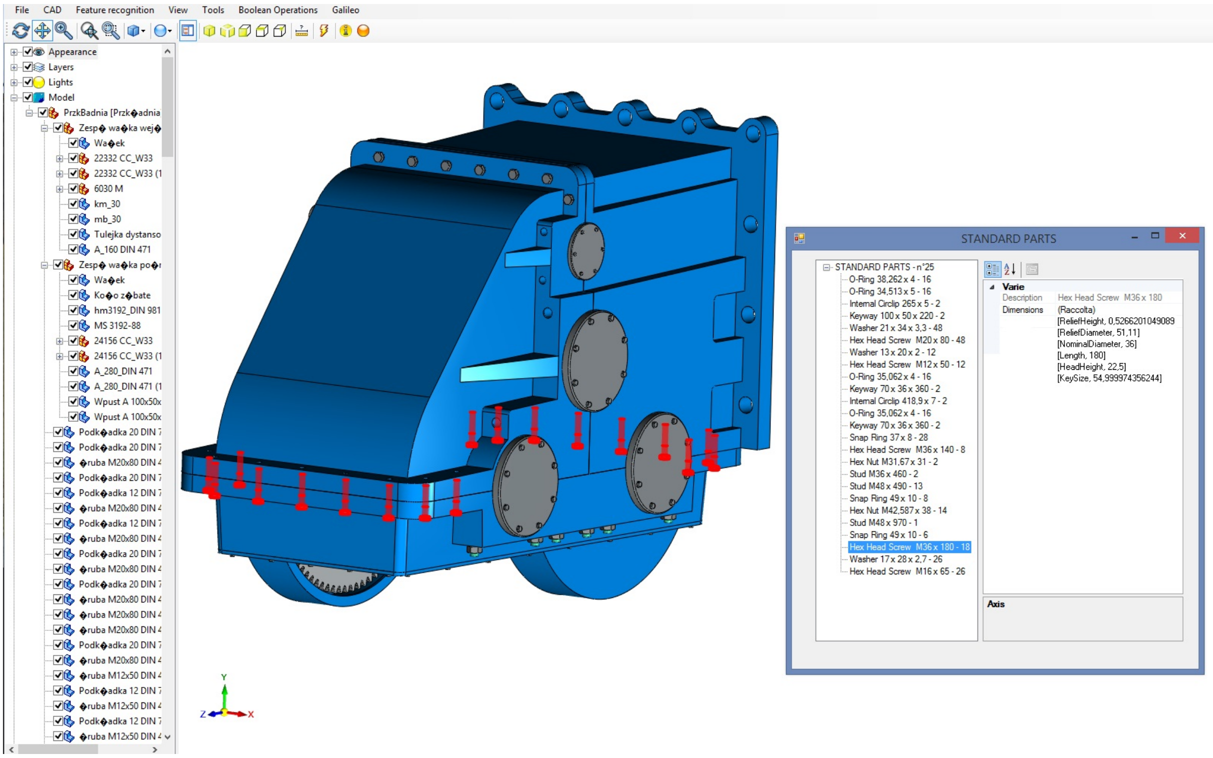


Figure 6: Visualization of the results in the developed tool.

6 CONCLUSIONS

In this paper a standard part type recognition algorithm is presented. Differently from existing methods, our approach is focused on the classification of those mechanical components having a defined function in the assemblies, and thus a specific engineering meaning, in order to enhance the semantics of the CAD models. In particular, eight categories of standard parts are considered, and they have been chosen according to their large employment in mechanics, i.e. screws, nuts, O-ring, washers, circlips, keys, studs and pins. The algorithm is based on the specification of standard engineering and design rules in terms of shape and geometric features of the parts. The recognition has been first evaluated on a test-set of standard parts. Then, it has been applied to industrial CAD model assemblies, to identify the standard parts included in the models. Results are promising: the validation proves that most of the parts are correctly recognized; the application shows that often more than half of the parts of a CAD assembly model are standard parts, and thus it would be useful to know them, along with their dimensions.

The main encountered issues are the challenging identification of standard parts with too general shape and the misleading interpretation of categories with similar requirements. Future works will address these problems, by introducing the probability of belonging to a given category (e.g. linked to the percentage of satisfied rules) and a further step in the recognition approach which, after finding a possible category of membership for a CAD assembly model part, will evaluate its adjacent components to confirm the presumed standard part type. Further classes of parts will be added to enhance the semantic interpretation of components.

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