Review on the Leveraging of Design Information in 3D CAD Models for Subassemblies Identification

Brigida Bonino[1] , Franca Giannini[2] , Marina Monti[3] , Roberto Raffaeli[4] ,

[1]DIME, Universitá degli Studi di Genova, brigida.bonino@ge.imati.cnr.it
[2,3]IMATI, Consiglio Nazionale delle Ricerche, [franca.giannini],[marina.monti]@ge.imati.cnr.it
[4]DISMI, Universitá degli Studi di Modena e Reggio, roberto.raffaeli@unimore.it

Corresponding author: Brigida Bonino, brigida.bonino@ge.imati.cnr.it

Abstract. In industrial manufacturing, both in the design and the production phase, the management of modern mechanical assemblies is becoming demanding due to their increasing complexity. The use of stable subassemblies concept constitutes a better alternative, which allows to independently treat smaller groups of the assembly's parts, also to achieve a parallel production. At this regard, several methods for automatic subassemblies identification, starting from the assembly CAD model, have been provided. However, most of the methodologies proposed rely on human intervention, especially in the model processing to make available essential data, while other details are ignored. After giving the definition of stable subassembly, this paper focuses on the application of stable subassemblies identification to industrial CAD models and highlights the issues arising. With the aim of ensuring a reliable CAD model analysis, starting point of the identification, the possible real engineering situations, both related to assembling methods and modelling techniques, are presented. Approaches to algorithmically address them are then described, with the help of two examples of mechanical assemblies.

Keywords: Subassembly identification, Stable subassembly, Assembly analysis, Industrial CAD model
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1 INTRODUCTION

Modern mechanical assemblies are increasingly complex, made of several parts and, in addition, customization are often required from industries: this results very demanding from the production point of view.

With the advent of Industry 4.0, emerging technologies have been studied and developed to support the manufacturing process in all its stages, with the objective of reducing the production time and costs [15], as well as increasing product quality and industrial collaboration [16]. In this regard, automatic Subassembly

Identification (SI) starting from an assembly CAD model is considered one of the topical problem in the industrial manufacturing field, and actually it is a relevant not fully explored research subject. The idea is to break down the assembly into groups of connected parts which can be treated independently of one another, avoiding to work with all assembly's parts simultaneously.

It is evident that the identification of subassemblies can be then exploited in several phases of a product life cycle. In the design phase, for instance, for the identification of reusable components [26]. Knowledge of significant subassemblies indeed allows designers to save time by reusing existing mature information. In maintenance or recycling operations, SI is a practice solution to reduce waste of resources [22]. In particular, if a target component has to be removed or fixed, it is convenient to split the assembly into smaller units just to focus and operate on a subassembly of interest, that is to say the one containing the target component. Subassembly identification, then, definitely finds application in the assembly manufacturing tasks. In literature, most of the Assembly Sequence Planning and Disassembly Sequence Planning methods widely exploit the assembly decomposition to limit the combinatorial explosion of the problem complexity [6, 21, 23]. The recognition of independent components contained in an assembly allows to simplify the assembly line. It is engineering reasonable, in fact, to plan the mounting of a complex product by functional modules. Operationally, each of the components can be produced separately, and then all of them are joined to make the final product. Further adding the stability hypothesis to the identified subassemblies, it is of particular interest to manage the production in parallel [1, 4]: place the production of a single product among multiple supplier industries or industrial robotic assemblers is certainly a solution to obtain a visible reduction in time and costs.

Significant progress has been made over the past decades with subassemblies and stable subassemblies identification; in literature, many methods have been put forward. However, it is very challenging to completely automatize the SI process, starting from the only assembly CAD model. Most of the methodology proposed therefore rely on human intervention, especially in the model processing to make available essential data. In addition, hardly ever, real industrial CAD models are taken into account, but rather simplified CAD models are employed as test-cases. It follows that many issues deriving from the assembly modelling don't arise and several real scenarios are omitted. Actually, only in few cases existing methods will yield optimal results if applied to complex industrial mechanical products.

The current research aims to develop a reliable tool for industrial applications, where automatic stable subassemblies identification is ensured, extending the approaches in the literature. This work, in particular, reviews the relevant literature and focuses on the use of industrial mechanical assemblies and on the deriving issues, which are not commonly faced. Ensuring a consistent CAD model analysis, where all the real engineering cases are taken into account and algorithmically addressed, is the main point to provide accurate SI methods.

In the following sections, we first investigate the key concepts involved in subassemblies identification and define what a stable subassembly is meant to be. In section 3, the techniques generally adopted in literature are further pointed out, dwelling on their limitations and potential improvements. Then, the problems deriving from the use of real industrial assembly CAD models are highlighted. Finally, exemplifications of these concepts are proposed in section 4. Section 5 ends the paper providing some conclusions.

2 STABLE SUBASSEMBLIES

Subassembly is a widespread concept which has been studied in many works in the last decades thanks to its increasing importance in industrial manufacturing applications.

Dini and Santochi [7] were the first to provide an accurate and comprehensive definition of subassembly in the early '90s. They stated that, given an assembly, a subassembly is a group of its parts which are connected to each other. It can not interfere with the other parts of the assembly in the assembly process. In addition, it is stable, in the sense that, if it is manipulated, it won't dismount and parts will maintain their mutual positions. However, the tools and the technologies adopted in that period are very coarse. It results that the given definition is quite strict and difficult to validate in practical applications, such as in subassemblies

identification, without a massive human intervention. This because it is required to evaluate a set of parts both in respect to each other and in respect to the entire assembly. As a consequence subassembly definition has been revised many times over the years. Depending on the specific focus and purpose of the single paper, weaker conditions are sufficient to establish whether a group of assembly's parts is a subassembly or not.
In the simplest cases, subassemblies are thought to be generic subsets of parts grouped only considering contacts and constraints information [5]. In other works, the definition of subassembly takes into account the assembly/disassembly process. For instance, Ko et al. [10] assume that a subassembly is a collection of components and all the assembly tasks among them. In [24] subassemblies are referred as assembly units made of less parts than the assembly, extracted considering the assembly process constraints. Watson et al. [25] speak about "logical subassemblies" as sets of at least two parts gathered together addressing part access and assembly precedence. The functionality notion is instead the focus in [12], where a subassembly is defined as a set of directly connected parts which achieves a particular function.

Notice that the requirement of the stability among the parts has been often overshadowed in the subassembly definitions. In fact, the stability concept has become a separate attribute of a subassembly, instead of an intrinsic characteristic of it, and, in subassembly identification works, it is than considered a discriminant factor for the evaluation of the resulting subassemblies and their feasibility. As well as for subassemblies, also stability assumes several meanings, in addition to that given by Dini and Santochi. Some works define stability by means of the degree of freedom of parts. In [3], for instance, the authors assess that a subassembly is indistinctly every group of connected parts and it can be partially stable, if at least one component is not totally blocked, or permanent stable, if components maintain their positions irrespective of orientation. In [17] the subassemblies are stable when the freedom of each part is zero. Other papers, evaluate stability based on the type of contact among parts, that is to say that a subassembly is stable if parts are fixed with connectors. In this perspective, Agrawal et al. [1] assume stable subassemblies to be sets of components which have fastened contacts and can not be easily removed individually; they adopt stability as the criterion for choosing some subassemblies among those identified rather than others. Smith et al. [20] state that a subassembly is stable if all the parts are supported by connections to adjacent parts or are gravitationally stable. Finally, stability can be seen as a quantitative measure. For example, Dong et al. [8] define stability through an index calculated on how parts deviate from their correct position while removing connectors.

It is evident that subassembly and stable subassembly concepts are indistinctly employed in literature with many different meanings, and this is confusing. In our research, a stable subassembly is a subset of assembly's parts that are mounted together before they are mounted on the assembly. That is, the joining of the parts of a stable subassembly can occur independently from its assembly in the final product. In particular, a stable subassembly can be considered an assembly itself, and reflects all the features of an assembly, such as the presence of one or more base components.
To be more accurate, our idea of subassembly stability should include several factors. Stability should indeed ensure that even by changing the orientation of the subassembly, it will maintain its configuration, parts will be gravitationally stable and maintain their mutual positions. It is to underline the previous statements do not necessarily imply that the degree of freedom of each part is zero. This last assertion can easily be exemplified by the case of a bearing. It is, in fact, a stable subassembly in the sense just defined, where the inner spheres can rotate on themselves while maintaining the type of contact with the two rings constant.

The following section provides an overview of the type of data and of structures adopted by the existing methods for stable subassembly identification.

3 SUBASSEMBLIES IDENTIFICATION METHODS

The criteria on which stable subassemblies identification techniques are based are multiple. However, most methods rely on a common approach, that will be summarised in the following steps: CAD model processing, base components identification, parts association to base components (Fig. 1). Then, every method has its specific features and pioneering choices.

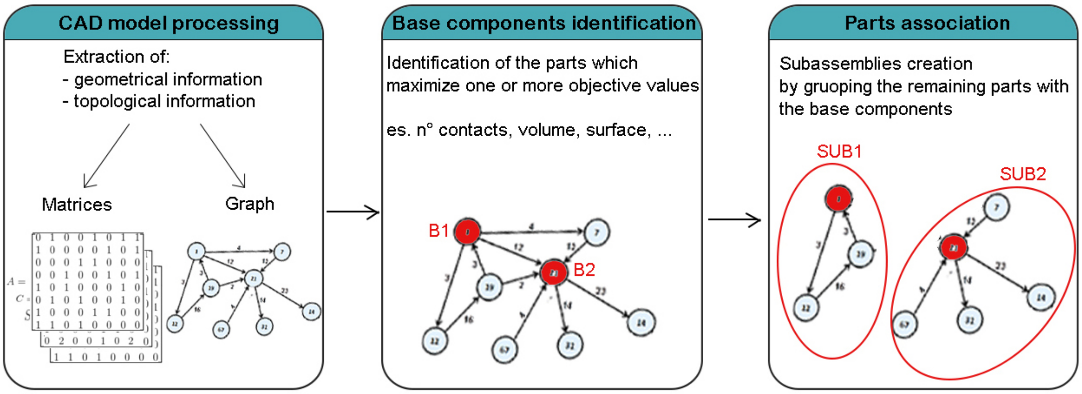


Figure 1: The three main steps in subassemblies identification methods.

3.1 CAD Model Processing

The processing of the assembly CAD model is the starting point: topological and geometrical information are extracted from it. The objective is to identify parts contacts and constraints as well as the possible directions for parts translations. It is a crucial stage of the process: the more accurate and detailed the data, the more reliable the subassemblies identification. The extracted data can be stored both in matrices and in graphs.
Indicated as M_n the set of square matrices of dimension n, where n is the number of components in the assembly, the mostly adopted matrices are of three types, and can be found with different names:

- Adjacency/Contact/Liaison Matrix: $A \in M_n$.
  A is a symmetric matrix, where the element a_{ij} represents the existence of the contact between parts i and j.
  Element a_{ij} usually assumes values 1 or 0, in some cases it can be an integer equal to the number of relationships between the two parts.
  The matrix can be transformed by considering the contacts according to the three axes x, y, z separately and making the element a_{ij} a 3-digital array.
- Constraint/Collision Matrix: $C \in M_n$.
  Element c_{ij} can be a 3-digital or 6-digital array representing constraints between parts i and j along the directions $d \in (\pm x, \pm y, \pm z)$ of the coordinate system of the assembly. $c^d_{ij} = 1$ means component j stops component i if moved in direction d, whereas $c^d_{ij} = 0$ means component j does not stop component i along d.
- Stability Matrix: $S \in M_n$.
  The element s_{ij} represents the stability or the type of fastening between any pair of components.

Usually are distinguished permanent stability due to external connectors, permanent stability due to mating features, partial stability or unstable pairs, with $s_{ij} \in \{0, 1, 2, 3\}$.

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 the following:

- Liaison Graph: it is the representation of contact information between any pair of parts, corresponding to the Adjacency Matrix. Two nodes are connected by an edge if the respective two parts have contacting faces.
- Blocking/Precedence Graph: similarly to the Constraint Matrix, it provides information about the blocking relationships within a component for a given direction (mainly the x, y, z axes) of assembly.
  The blocking graph is a direct graph where the predecessors of a node are blocked by the corresponding node along that direction.

These graphs can be enhanced, for example, making them weighted graphs. In the simplest case, weights are given by the type of contact (i.e. $w = 2$ if the parts are fastened by connectors, $w = 1$ if parts have only contact coupling relationship, $w = 0$ if parts are not in contact), and represent the same data expressed by the Stability Matrix. In more specialized cases, weights are calculated based on the evaluation of different factors, such as the combination of functional, structural and process constraints.
In general, when dealing with assemblies made of many parts, matrices and graphs have big dimensions and the increase of computational time and costs is the consequence. A simplification stage is then proposed in different works: the size of the data structures is reduced by removing all connector elements, which actually are standard components and can be treated separately.

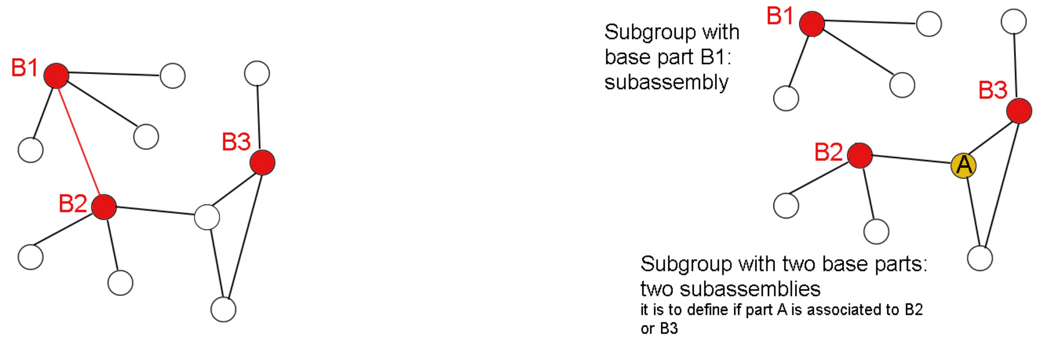
3.2 Base Components Identification

In order to detect subassemblies, the concept of base parts is introduced. Base parts are m components of the assembly starting from which subassemblies are generated. The number m is always set in advance, and this can be a limitation. The choice of base parts can happen in different ways, either manually selected or automatically according to various criteria. The search for base parts is performed on the matrices and/or graphs resulting from the CAD model processing. In general, base parts can correspond to the components having highest degree of connections, although contact criterion is not enough for a right classification. As a consequence, the maximization of an objective function is frequently introduced, e.g. [5, 24]: it involves the evaluation of some heuristic measures, like number of contacts, volume, dimensions and boundary surfaces.

3.3 Parts Association to Base Components

Once the base parts are identified, the generation of subassemblies follows. There exist two different ways for associating parts to base components:

- Iterative Optimization Algorithms are provided to partition the assembly [2, 10, 11]. In this case some fitness values are defined and a fitness function has to be minimized. At each iteration the clusters' center and members are updated, until a certain threshold is reached.
- Connections between all base parts are removed, some subgroups of parts are therefore obtained [5, 21]. If any of these subgroups includes only one of the base parts among its parts, it implies that this subgroup is already a subassembly. On the contrary, if a subgroup includes two or more base parts, it has to be subdivided in as many subassemblies as the number of base parts (Fig. 2). To define the membership of a part to a base part's group, some evaluations are done analysing the previously described matrices/graphs.



(a) Liaison graph with three base parts.

(b) Remaining subgroups of parts after removing contacts among base parts.

Figure 2: Example of part association to base components by removing connections.

3.4 Limits and Possible Improvements

In most works, only few limitations of the presented methods are mentioned. On the one hand, some reported issues are the excessive human intervention, the choice in advance of the number of base parts and the high computational cost, on the other hand not fully realistic assumptions are made, either for the information extraction from CAD data and on the assembly operations, like precise mating between the faces of CAD parts in contact and the possibility of translating parts only along the x, y and z axes.

Besides, we want to point out that, also parts' contacts evaluation is an aspect that can be improved. In fact, merely checking the existence of the contact between two parts is limited, as well as considering the contacts according to the three axes x, y, z provides incomplete information. Just think to encapsulated cylindrical components: in this situation is not meaningful to only assess the existence of the contacts along the x, y and z axes, because it can not suggest that a part is completely inserted in one another. Rather, it is important to know the common axis of the cylindrical components, and if their whole circular surfaces, or only a portion of them, are in contact.

Intuitively, a first way to enhance this lack of useful information during the CAD processing and matrices extraction is to distinguish between different types of contacts, each of which will have its specific attributes included. For example, if the contact is planar, we will calculate the number of faces in contact and their normal vectors. If, instead, the contact is cylindrical, we will record the faces' axes. Contacts can also be simultaneously planar and cylindrical; e.g. a screw has planar and cylindrical contact with the part in which is inserted: the body has cylindrical contact with the hole's face, while the head has a planar contact with the external face of the part.

Finally, one more aspect that has to be taken into account in the future method formulation is the following. Performing subassembly identification through the scheme described above implies that all the assembly's parts are associated with one of the base parts. However, this is not totally correct. In fact, when analysing the definition of stable subassembly given in Section 2 and manually identifying subassemblies on some test-cases, we notice that once identification is complete, not all parts of the assembly will have been included in one of the recognized subassemblies. Some parts will be excluded from the grouping, because they exactly are the parts that connect the identified subassemblies to each other.

4 ISSUES IN PROCESSING INDUSTRIAL CAD MODELS

In literature, the SI methods efficiency is, in general, assessed on simple assemblies made of few parts, also relying on the human intervention to make available some essential information. In fact, the test-cases employed are error free CAD models with a limited number of parts, where the knowledge of standard components (i.e. fasteners and connectors) is taken for granted and other details are ignored. However, to provide robust and effective tools for industrial application, experiments on real business product models should be taken into account, and working with these models results very demanding.

In this section we illustrate the issues that arise when dealing with CAD models of real assemblies in the subassemblies identification. It is to notice that the main problems are encountered during the CAD model analysis, when the objective is to fully automatize the extraction of the necessary information for the identification, such as reliable contacts and constraints matrices or graphs, starting point of subassembly detection algorithms.

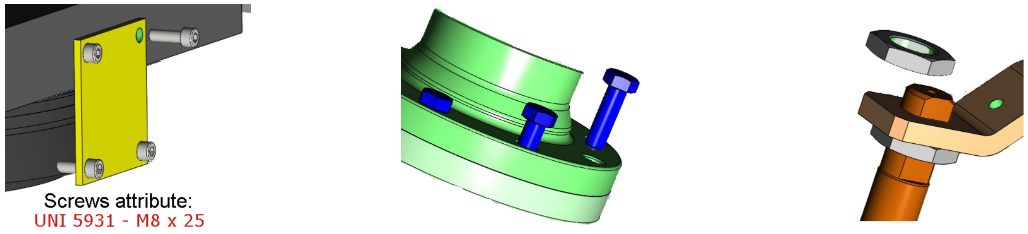
4.1 Methods for Assembling Parts

In mechanical assembly manufacturing, several methods for connecting parts can be adopted. Each mode can be represented with different techniques in the CAD model, both explicitly included in the assembly as its components, and implicitly as data hidden in parts' attributes or geometric dimensions. It is challenging to algorithmically extract all these information only having the assembly CAD model, geometric features and some semantic data. Actually, to the best of our knowledge, no works construct the assembly contacts matrix taking into account all these possibilities.
In the following, the various methods are reported with indications on how they are normally modelled and how can be detected from CAD data, as summarised in Table 1:

Method for assembly	Possible ways for the detection
Threaded components	Standard parts Features recognition Cylindrical contacts and diameters analysis
Weldings	Contacts analysis
Interference fit	Dimensional tolerances analysis
Deformable components	Standard parts Geometry and shape analysis

Table 1: Summary table of the methods for assembling parts.

a) *Threaded components:* an important assembling mode involves the use of threaded components, namely fasteners such as screws, bolts, studs, etc. This type of connections is commonly considered in literature. Some SI algorithms remove fasteners from the contact matrix, to reduce the number of parts to analyse, e.g. [5], others identify fasteners to evaluate the strength of the contact among two parts, e.g. [2, 11]. Most of the time, threaded components are in fact modelled as standard components and are consequently easily recognisable by means of some semantic attributes, which refer to international standards. That is to say, if some codes (e.g. UNI, DIN, ISO, etc.) are found in the part description, the part can be classified as a specific fastener. Nevertheless, parts' attributes may be missing or lost and the identification is no more trivial. Similarly, being standard components, in some cases they are even not modelled in the assembly or idealised with simplified geometry, as discussed in the next section.

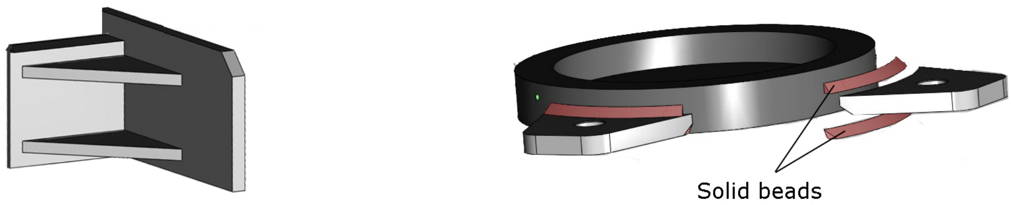


(a) Screws as standard components. (b) Screws. (c) Nuts.

Figure 3: Examples of threaded components in CAD models.

A way to infer the presence of threaded components is to analyse assembly's features, such as holes and cylindrical contacts among parts. In particular, if coaxial threaded holes exist between two distinct parts having planar contact, and both the parts are in contact with a threaded cylindrical element, this element can be classified as a fastener. Then an additional confirmation of the classification can rely on the diameters analysis: in CAD, threaded fasteners, in fact, are usually modelled with some conventions. These state that the nominal diameters of a threaded component and of the associated hole are the same, although they are modelled with different values, which respectively refers to the maximum and the minimum diameter of the thread.
In case these standard components are not modelled explicitly in the assembly, their presence in the final product can be guessed by the presence of two coaxial threaded holes in contact in adjacent parts. While when idealised, they may give rise to volumetric intersection with the part in contact.

b) *Weldings:* a common assembling process is welding. Weldings detection is very useful in subassemblies identification: welded parts behave as a single part, thus can be merged together reducing the number of parts to consider in the algorithms, or even they may constitute an independent stable subassembly. In the assembly CAD model, weldings may not be explicitly represented (Fig. 4a), making an automatic recognition very hard. A first way to recognize two welded parts is by analysing their contact, like in [18], but barring those couples of parts which are already connected by threaded components.
Another different representation of weldings that may be found in industrial CAD models is by means of solid welding beads modeling (Fig. 4b). This is a less common practise, but has certainly to be mentioned.



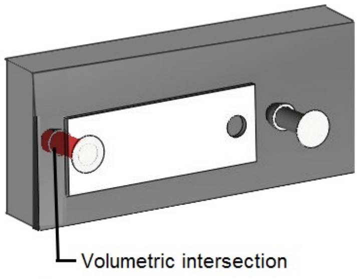
(a) Weldings not explicitly represented. (b) Weldings with solid beads.

Figure 4: Examples of weldings in CAD models.

c) *Interference fits:* two parts can be assembled only because wedged together due to their dimensions, namely the solid part is slightly larger than the hollow one. This situation in not evident from the simple geometry of the CAD model. The two parts are, in general, modelled with congruent sizes, but this information can be implicitly available as dimensional tolerances, reading them can suggest the presence of the interference fit. In fact, these attributes refer to the deviation of the geometric visible value from the nominal dimensions. On practical point of view, interference fit may require a deformation of at least one of the two parts involved. However, this assembly mode should not be confused with mounting through deformable components (see next item). One indeed connects only two parts, the other connects two parts through a third deformable component.

d) *Deformable components:* mounting can happen through the deformation of some parts, by enlarging or tightening them. Two kinds of deformation have to be distinguished: *temporary deformation* and *permanent deformation*. The first type occurs when the component gets deformed just during the mounting operation, after which it returns to its original form. Clips, seegers, gaskets and O-rings are some examples of temporary deformable components (Fig. 5a). The latter type of deformation is when a component, like rivet, changes its form definitely and this assures the joint of two distinct parts (Fig. 5b). To separate the two joined parts may be then necessary to break the deformed component. Mounting through deformation is not mentioned in any work, consequently the associated connectors are treated as common parts, although they are meaningful in the assembly interpretation. The presence of a deformed connector may help in the evaluation of the contact between two parts, suggest if a part belongs to a subassembly or another, or be decisive in the subassembly stability assessment.
If the deformable connectors are not represented as standard components in the CAD model, a geometric analysis is fundamental in the identification of connectors like gasket and O-ring. In fact, they are modelled by means of planar ring faces, torus and coaxial cylinders. Also the material, when attached, is a discriminant factor in the identification.

(a) Internal and external gaskets.



(b) Rivets (which generate volumetric intersections with the part).

Figure 5: Examples of deformable components in CAD models.

4.2 Techniques of Modelling

In CAD models, the choices of the designer certainly influence the product representation, and this makes it difficult to handle all assemblies correctly. In this context, we can list some of the factors that must certainly be taken into consideration, which are summarised in Table 2:

a) *Missing components:* CAD models have often missing parts, with the aim of making the model leaner

Issue in CAD modelling	Design motivations	Possible ways for the detection
Missing components	Make the model lighter	Contacts analysis Holes' coaxiality analysis
Modelling errors	Format translation Numerical errors	Volumetric interference analysis Clearance analysis
Imported parts	The components are provided by external suppliers	Parts' attributes analysis Multibody structures identification
Flexible parts	Existence of parts with variable shape	Materials attributes analysis Volumetric intersections analysis
Idealized parts	The details of the parts are not of interest	Artificial Intelligence methods Parts' attributes analysis
Extra volumes	Welding beads are modelled as solids	Parts' attributes and descriptions analysis

Table 2: Summary table of the techniques and issues in CAD assembly modelling.

and lighter; this may refer to different situations.
On the one hand, a common practice is not to physically include connectors and fasteners (screws, bolts, studs, gaskets, pins, etc.) because they are standard components and their geometry is uniquely defined by international conventions. Hence, the existence of a not modelled standard component can be identified through some recurring schemes and specific features: for instance, coaxial holes among two parts, threads and diameters analysis.
On the other hand, it could be a choice of the designer to omit some parts. Among these, insignificant parts or parts external to the specific product portion under design, but interfacing it (chassis, support base component, etc.).

b) *Modelling errors:* it happens that CAD models include errors. Some components can in fact be badly modelled or wrongly positioned, due to format translation numerical errors, as well as inattention of the designer. It follows holes misalignment and also the generation of false features, like intersections (volumetric interference) or, vice versa, empty spaces (clearance) among parts [9, 14], cause of misleading interpretation of the assembly or missing detection of contacts.

c) *Imported parts:* some components in CAD models may themselves represent stable subassemblies, this is the case of imported objects, externally purchased. These components are customarily modelled as single parts, because it is sufficient to show just their overall dimensions and shape into the assembly, rather than their complete geometry and details. During the model analysis, imported parts can be recognized through specific codes or, in some cases, thanks to their multibody structure.

d) *Flexible parts:* industrial mechanical assemblies can contain flexible parts, for example electric cables, belts or springs. It depends on the designer how this kind of components are modelled in CAD, since they may be represented in the resting or in a stressed (stretched or compressed) state. Depending on the chosen representation, the flexible part may give rise to volumetric intersections with the adjacent parts.

e) *Idealized parts:* it can be a designer's choice to model parts at different level of details. The shape of some components can thus be idealized in the CAD model, making very challenging their identification. In fact, a simple abstracted shape may correspond to several objects and thus it is not sufficient to indicate what the component is. Moreover, also the representation of parts' contacts is affected. An idealized component can only be deduced from its usage in the assembly model; possibly by defining some rules based on a priori engineering knowledge [13] or by exploiting Artificial Intelligence methods.

f) *Volumes not corresponding to parts:* in CAD models, volumetric objects not corresponding to real components of the assembly can be found. This is the case, for example, of the solid modelling of welding beads cited in the previous section (Fig. 4b). It is important, for the purpose of providing a correct assembly analysis, to recognize this supplementary parts, precisely because they have not to be considered as normal components, but rather they have to be associated with mounting operations.

5 EXAMPLES

In order to better visualize the issues mentioned above and demonstrate that they can be recognisable situations, in this section we provide two examples of CAD models of assemblies supplied by industrial companies, which can not be automatically treated by the methods in literature because exhibiting some of the issues presented in the previous section. In the following, the included stable subassemblies will be described together with the issues that they present for the successful application of the SI methods existing in literature.

5.1 Example 1: Belts Drive Mechanism

The CAD model of a belts drive mechanism for motion transmission is first presented (Fig. 6).

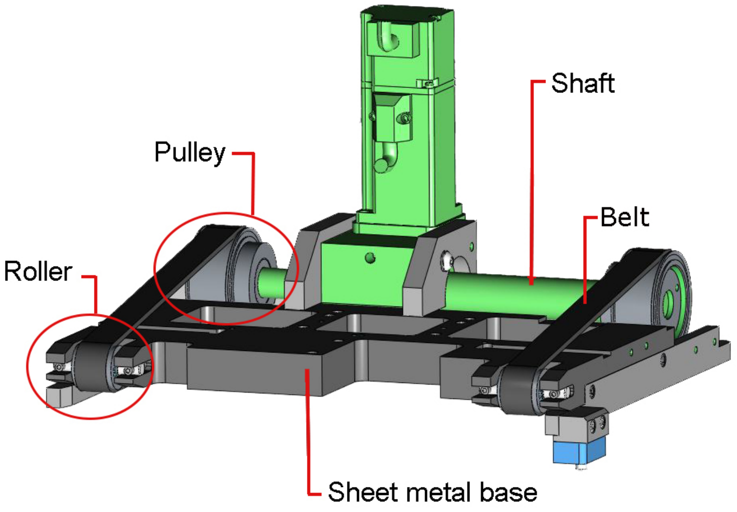


Figure 6: CAD model of a belts drive mechanism for motion transmission.

It mainly consists of two flat belts, each of which links a pulley and a roller. The pulleys are mounted on a common main shaft, while the rollers have separate shafts. It is evident from the sheet metal base with empty holes that this assembly isn't a finished product itself, but rather it is a component that will be installed on a more complex assembly.

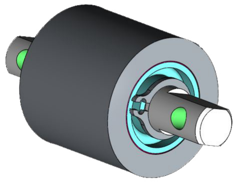


Figure 7: Roller subassembly.

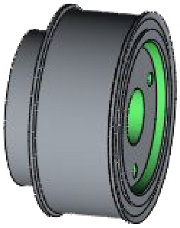
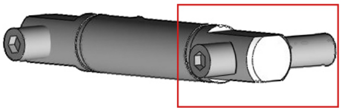


Figure 8: Pulley subassembly.

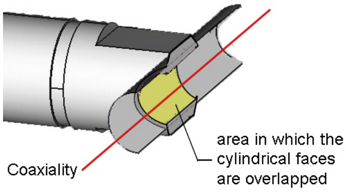
Analysing the assembly, it can be assumed that the two rollers (Fig. 7) and the pulleys (Fig. 8) could theoretically be stable subassemblies, in the sense defined in Section 2. In fact, they can be assembled separately, and then mounted on the mechanism; if manipulated, these objects don't dismount. Respectively, in the first case, the bearings and the shaft are blocked inside the external cylinder of the roller by the two C-clips, which prevent translations along the axis. In the second case, the parts that make up the pulley are locked together by interference fit.

Besides, the roller subassembly clarifies the assertion that a subassembly is stable even if the degree of freedom of each part is not zero. Namely, the external cylinder, can rotate around the shaft, but the relative positions of parts are constant thanks to the fixing of the clips.
The model of the belts drive mechanism is also meaningful to point out the difficulties that can be faced during the CAD processing. Data extraction is indeed very challenging, since it presents several of the cases mentioned in Section 4, not commonly treated in literature.

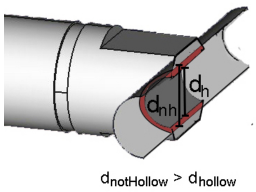
As far as the mounting techniques are concerned, both threaded components and deformable components are found.
Although some of the threaded connectors are represented as standard components, thus they are easily recognisable by means of the codes, the model contains also other types of threaded fasteners that must be inferred in a less intuitive way. Meaningful examples are the pins inserted in the rollers' shaft. We can algorithmically classify them as threaded fasteners by exploiting the geometric assembly features, checking the following items (Fig. 9):



(a) Couple of parts analysed: pin in shaft's hole.



(b) Coaxial and overlapped cylindrical faces.



(c) Not hollow and hollow diameters difference.

Figure 9: Threaded component classification.

1. the cylindrical hollow face relative to the hole and the cylindrical not hollow face of the pin are coaxial and overlapped. The contacts are identified by evaluating if the faces' bounding box are somewhere superimposed and by comparing the length of faces' diameters.

2. the hollow face has a smaller diameter than the not hollow one. Namely, in the shown case, the diameter of the hollow face is $d_h = 3.3$ while the one of the not hollow is $d_{nh} = 4$;

3. the hollow face is also threaded. Specifically the thread is of type M4, where 4 is exactly the diameter of the pin.

It follows that the part to which the not hollow face belongs is a threaded component. This is the general scheme we adopt to identify every threaded component.
Deformable components are then found: the C-clips in the rollers are an example. They can be identified by means of their particular shape and then classified as deformable connectors [19]. In the current assembly, the knowledge of the C-clips presence is a key point for the rollers stability assessment, since they serve to block all the subassembly's parts.

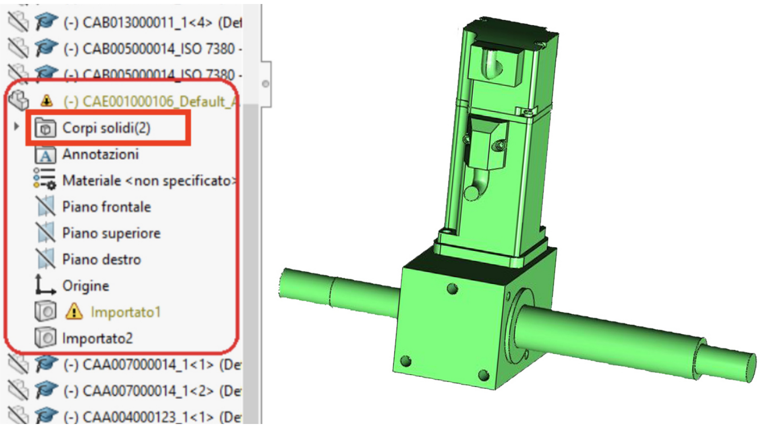


Figure 10: Multibody structure of an imported component in the CAD model.

Moving on to the discussion of the techniques of modelling, imported parts are included in the CAD model of the mechanism. This is the case of the main shaft on which the pulleys are mounted. It is evident from the part inspection that, even if it is modelled as a simple component, it has a multibody structure (Fig. 10). In response to this analysis, we can thus state that also the part containing the shaft is actually an (imported) stable subassembly.

Finally, the two flat belts are certainly an example of flexible parts. The fact that, in the CAD model, they intersect the parts on which are looped, rather that simply having one face in contact, is a first hint for their classification as flexible parts.

5.2 Example 2: Gripper Mechanism

The second example we want to analyse is the CAD model of a gripper mechanism (Fig. 11). It allows us to illustrate some of the remaining situations, such as weldings and missing components.

In this model we can distinguish two major components, potential independent subassemblies, connected by a stud. The upper unit is a support component which will be then mounted on the rest of a bigger assembly

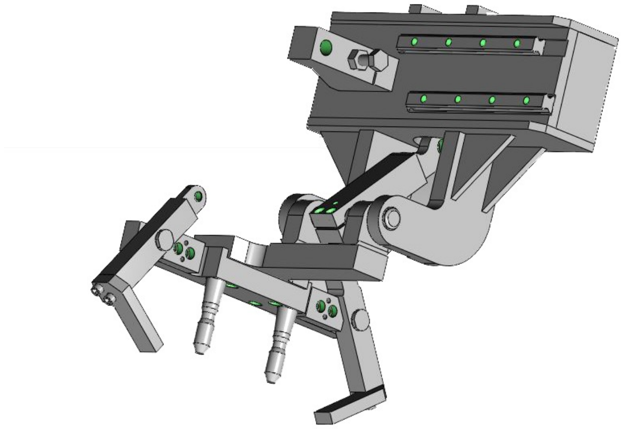


Figure 11: CAD model of a gripper mechanism.

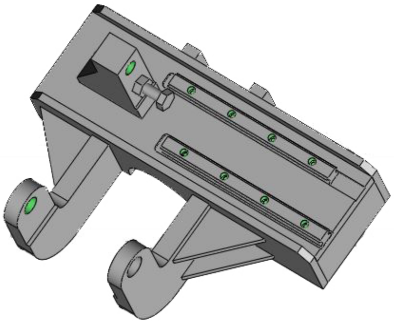


Figure 12: Support component subassembly.

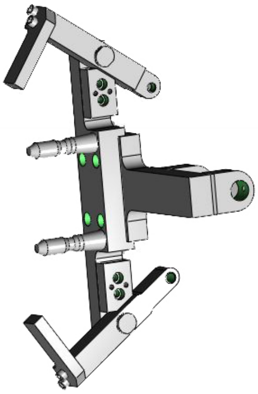


Figure 13: Gripper subassembly.

(Fig. 12); the lower unit is the gripper itself (Fig. 13).

In the presented gripper model a large use of weldings to join parts can be found. The support component's parts, with the exception of a few, indeed, are all welded together and can thus be merged in a single part during the processing phase (Fig. 14). Weldings are nevertheless not explicitly represented in the CAD model and their automatic recognition is very challenging. We may deduce the presence of weldings by evaluating parts contact. In particular, two main conditions have to be satisfied at first:

1. the parts must have two planar surfaces in contact, these can be either an entire face of the part or only a portion of it;
2. there must not be coaxial holes among the two parts or a third components with cylindrical contact with both the parts. These two situations, in fact, would imply the presence of fasteners, such as screws.

Notice that the two conditions are certainly necessary to infer weldings, but not always sufficient. Thus a

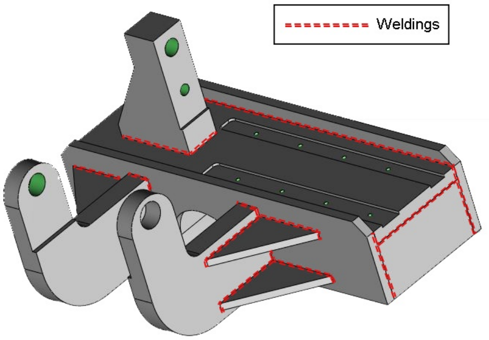
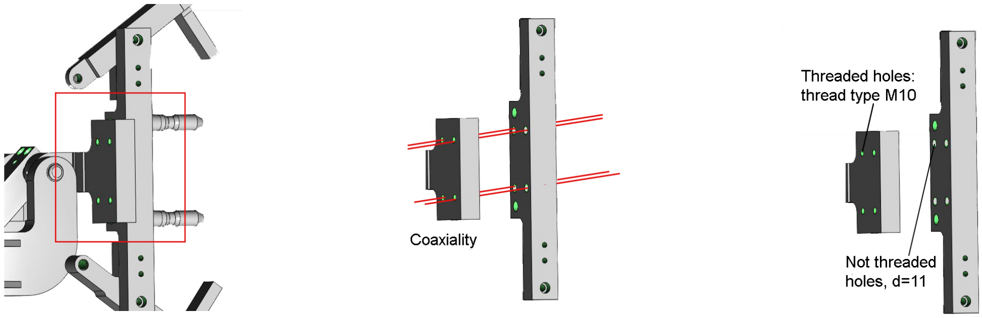


Figure 14: Welded parts in the gripper mechanism: they can be considered a single component.

confirmation from the user can be considered, which is anyhow less demanding than the completely user driven specification of the welds.

The second issue we want to highlight through the current example is the miss of components. Most fasteners are actually not modelled in the presented CAD. This design choice is evident from the presence of empty threaded coaxial holes, visible, for example, in some of the gripper's parts (Fig. 15). More in detail, to identify not modelled standard components, the general scheme is as follows:

1. there exists two parts with a planar face in contact and coaxial holes
2. the holes are empty, in the sense that there is no components with a cylindrical not hollow face in contact with any of the holes' walls.
3. In case only one of the two holes is threaded, the diameter of the other hole is slightly bigger than the nominal diameter of the thread. Namely, in the shown case, the thread is of type M10, and the diameter of the not threaded hole is 11.



(a) Couple of parts with planar face in contact.

(b) Four couples of coaxial and empty holes.

(c) Threads and diameters analysis.

Figure 15: Identification of not modelled threaded fasteners.

Finally, not only fasteners but also some external parts are omitted from the model. These parts are probably not relevant for the designer, but they would be significant in the model analysis. Some misleading situations, in fact, arise. For instance, in the back of the support component, there is a part floating in the void, because it should be connected to a not modelled component of the rest of the assembly (Fig. 16).

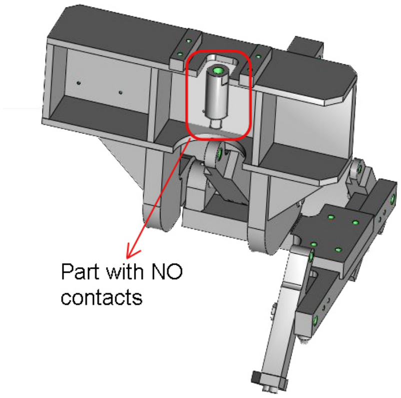


Figure 16: Part floating in the void due to parts omission.

6 CONCLUSIONS

Automatic stable subassembly identification is an industrial manufacturing topic where research is active. However, many works are limited by the fact that they actually consider only few of the situations found in real engineering. A detailed analysis of the CAD model is, instead, crucial for the outcome of the SI methods. In this context, the paper points out the issues resulting from the processing of industrial CAD models, that are usually overlooked. Two main classes of problems are defined: on the one hand the several existing ways for assembling parts which may have effect on the CAD model, on the other hand the techniques of modelling, which may also depend on the designer's choices. Some methods and general schemes to allow an algorithmic extraction of all these information are then illustrated.

Our future research aims to develop a reliable tool for industrial applications, where automatic stable subassemblies identification is ensured. Since the project is carried out in partnership with the Italian company Hyperlean (https://hyperlean.eu), the tool is meant to be a module of their industrial software LeanCOST, allowing at the same time the possibility to the user to confirm or modify the provided results. The presented industrial CAD models analysis and the described methods to address all the most common real situations guarantee an exhaustive automatic data extraction, and will be at the base of our future works.

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ORCID

Brigida Bonino, http://orcid.org/0000-0002-4264-3958
Franca Giannini, http://orcid.org/0000-0002-3608-6737

Marina Monti, http://orcid.org/0000-0002-1627-3551
Roberto Raffaeli, http://orcid.org/0000-0003-0301-454X

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