Research article

Assembly planning with automated retrieval of assembly sequences from CAD model information

Roberto Viganò
Mechanical Department, Politecnico di Milano, Milan, Italy, and

Gilberto Osorio Gómez
Design Engineering Research Group, EAFIT University, Medellín, Colombia

Abstract

Purpose – The purpose of this paper is to define an approach to extract the liaison graph from a 3D CAD model and analyze a method to find at least a feasible assembly sequence for the product. The method could be useful to search the optimal sequence of assembling for a product, by comparing different sequences extracted in automatic mode from a 3D CAD model.

Design/methodology/approach – The method proposed analyzes the liaison graph extracted, in order to obtain the possible assembly sequences for the product under study. The extraction of the sequences is based on some attributes and parameters of the graph.

Findings – By means of the method proposed it is possible to obtain in automatic mode the liaison graph of an assembly 3D CAD model. Moreover, the study of the graph obtained allows the definition of all the assembly sequences for the product. Finally, it is possible to analyse the sequences found to select the optimal sequence.

Research limitations/implications – The major limitation of the approach is, actually, the great number of impossible sequences that are extracted. For this, a little intervention by the user is required.

Practical implications – The application of the method allows the manufacturer to analyze and study the optimal assembly sequence without the direct use of a CAD system. The approach could be used at the early stage of the design process and by means of the database of the PDM/PLM systems.

Originality/value – The approach proposed in the paper is an original method to extract a liaison graph from a 3D CAD model. The approach to extract the assembly sequences was compared with other methods and good results have been obtained.

Keywords Assembly, Modelling, Process planning, Assembly sequences planning, Assembly modelling

Paper type Research paper

Introduction

Assembly process is considered as a very important cost factor into the total product cost and its planning methodology plays a central role in product and assembly system design. According to Ritchie *et al.* (1999), the analysis of assemblies is fundamental to modern manufacturing economies, so that around 50 per cent of the product cost is attributed to the assembly stage (Fan and Dong, 2003). The problem of assembly planning includes the study of both the assembly sequences and the assembly tasks and it is traditionally an intuitive, heuristic and lengthy process based on the skills and the subjective experience of a manufacturer. The character of the task often does not permit the exploration of all the alternatives, reducing the search to few subjective solutions. Therefore, to improve the manufacturer's assembly plan definition, an analysis of all feasible assembly sequences for a product could be useful. This analysis can help the manufacturer to choose an efficient assembly sequence able to allow the reduction of the overall assembly process costs by reducing the number of the fixture and tool changes or the number of the reorientations during assembly tasks (Pan, 2005). Unfortunately, this analysis could often result impracticable at industrial level because of the longer time required to generate all the feasible assembly sequences of the product.

Over the past 25 years many research projects have been conducted to identify both the feasible assembly sequences and the best assembly tasks, developing querying-based methodologies where experienced skilled staff is interrogated during the assembly definition process. So the feasible sequences are generated through the identification of technical and oriented decision rules or precedence relationships among the parts (Homem de Mello and Sanderson, 1991; Demoly *et al.*, 2011; Xing *et al.*, 2007). Many approaches start from a well-defined product architecture, just like those proposed by Bourjault (1984) and De Fazio and Whitney (1987), while computer aided

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design (CAD)-based approaches, as those proposed by Gottipolu (Gottipolu and Ghosh, 1995) and Lin (Lin and Chang, 1993), require a previous knowledge of the assembly sequence and/or proper definition of assembly mates, which still requires the human intervention.

Based on the authors' previous work, this document presents an approach to automatically extract, at least, a feasible assembly sequence for a product directly from its CAD model without human support, independently of the adopted modelling technique and considering a concept level of the model, evaluating in a hierarchical approach the importance of both sub-assemblies and components. This approach is useful to define assembly sequences in early stages of design in order to allow and to improve the application of design methodologies, just like design for manufacturing and assembly, reducing both costs and lead-time.

After a brief analysis of the problems connected to the extraction of the liaison graph of the parts of the product assembly from a CAD model, a procedure for automatic assembly sequences generation is explained using a basic example and, finally, a bibliographic comparison example is presented in order to show the usefulness of the method.

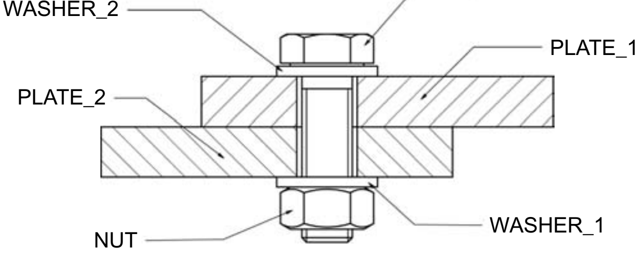
Assembly liaisons

The theory of assembly sequence analysis (ASA) (De Fazio and Whitney, 1987) is oriented to define feasible assembly sequences for a product with defined architecture, analysing possible assembly combinations. The two different objectives of ASA theory are: find one or all possible feasible sequences for the assembly of a product. The basic approach to problem solving in ASA is the systematic search into the problem domain. Considering that the definition of the assembly sequence can be addressed through a combinatorial approach, based on the total number of parts of the product, it shows the possibility of an explosion in the number of possible solutions. In fact, without any other information, the number of the possible combinations $\boldsymbol{C}$ among the $\boldsymbol{n}$ parts of a product, in order to define all its assembly sequences, is:

$$C = n!$$

So, for the assembly with six components shown in Figure 1 (Zha, 2004) the number of the possible combinations is 720. To reduce the number of the combinatorial sequences it is possible to follow two ways. The first, adopted in many studies (Kim *et al.*, 2004; Roy and Bharadwaj, 2002; Liu and Nnaji, 1991; Whitney *et al.*, 1999), is based on the direct lecture of the drawing and the creation of the liaison graph with the aid of the users. Along this way is easy to observe that, for the previous example, the obtained liaison graph is that one shown in Figure 3 and the number of the assembly sequences, as reported in Table I, is reduced to 12.

Figure 1 Bolt-nut plate fixing



The second one is devoted to extract the liaison graph from the CAD model using the assembly parts sequence obtained through the CAD assembly features tree or the graph derived by the analysis of the mate and align commands used to connect the parts into the modelling software.

For example, Arun and Rao (2010) proposed an application programming interface for a CAD software to extract assembly related data, while Su (2009) presented an integrated software prototype system to find out the geometric assembly precedence relations based on the assembly CAD model. But anyway, in none of them, the assembly sequence is automatically generated and Wang *et al.* (2009) arrive to conclude that human intervention is required to extract the assembly information from a 3D CAD model.

In conclusion, most previous researches related to computer tools require some human interaction and depend on the modelling technique to obtain specific information for their functionality. This issue is due to both the nature of CAD systems and to the methods used in the creation of the virtual assembly models, so it is very difficult to base the generation of the sequences on the assembly relationships entered by the user. In fact, for the assembly shown in Figure 1 it is possible to foresee the following relationships, considering the plate 1 fixed (Figure 2):

- mate upper face of plate 2 to the bottom face of plate 1;
- align the axis of the hole of plate 2 to the axis of the hole of plate 1;
- mate the face of the washer 2 to the face of plate 1;
- align the axis of the washer 2 to the axis of the hole of plate 1;
- mate the face of the washer 1 to the face of plate 2;
- align the axis of washer 1 to the axis of the hole of plate 2;
- mate the bottom face of the bolt to the face of the washer 2;
- align the axis of the bolt to the axis of the washer 2;
- mate the face of the nut to the face of the washer 1; and
- align the axis of the nut to the axis of the bolt.

The assembly thus created allows to automatically extract the relationships among the parts and to generate the liaison graph of Figure 3, but just modifying the relation number 8, for example aligning the axis of the bolt to the axis of the hole of plate 1, it is possible to obtain a different graph and a major number of assembly sequences (Figure 4 and Table II).

This simple example shows how different modes to assembly the same parts bring to hyper – constrained graphs, while in other kind of assembly CAD models it often happens that the number of constraints is lower than those required for a good automatic sequences definition. In this way, it is very difficult to obtain a reliable liaison graph for further development of a study for feasible assembly sequences through the analysis of standard assembly relationships, even though the designer is aware of assembling the different parts in a correct order into the modelling software.

In order to define the liaison graph of an assembly model of a product, the authors think that better results could be obtained considering the spatial interaction among the parts through an automatic inquiry, by means of CAD tools, of either global clearances of zero value or interferences among the parts. This approach is based on the assumption that the

Table I Assembly sequences of bolt-nut plate fixing

No.	Assembly sequence						Feasibility
1	PLATE_1	WASHER_2	BOLT	NUT	WASHER_1	PLATE_2	No
2	PLATE_2	PLATE_1	WASHER_2	BOLT	NUT	WASHER_1	No
3	WASHER_1	PLATE_2	PLATE_1	WASHER_2	BOLT	NUT	Yes
4	NUT	WASHER_1	PLATE_2	PLATE_1	WASHER_2	BOLT	Yes
5	BOLT	NUT	WASHER_1	PLATE_2	PLATE_1	WASHER_2	No
6	WASHER_2	BOLT	NUT	WASHER_1	PLATE_2	PLATE_1	No
7	PLATE_1	PLATE_2	WASHER_1	NUT	BOLT	WASHER_2	No
8	WASHER_2	PLATE_1	PLATE_2	WASHER_1	NUT	BOLT	Yes
9	BOLT	WASHER_2	PLATE_1	PLATE_2	WASHER_1	NUT	Yes
10	NUT	BOLT	WASHER_2	PLATE_1	PLATE_2	WASHER_1	No
11	WASHER_1	NUT	BOLT	WASHER_2	PLATE_1	PLATE_2	No
12	PLATE_2	WASHER_1	NUT	BOLT	WASHER_2	PLATE_1	No

Figure 2 CAD assembly constraints to the bolt-nut plate fixing

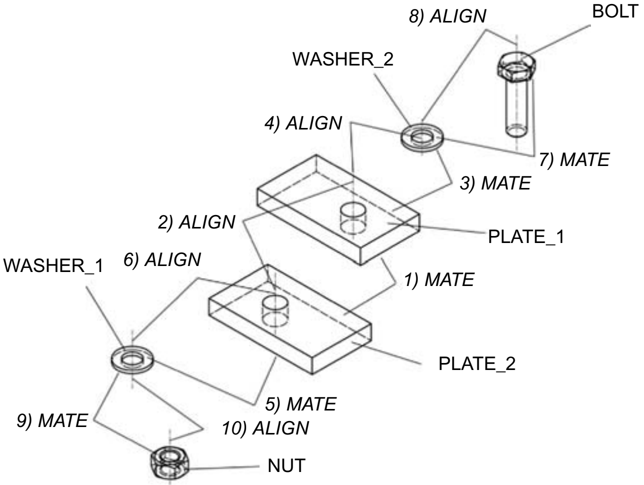


Figure 3 Liaison graph of bolt-nut plate fixing

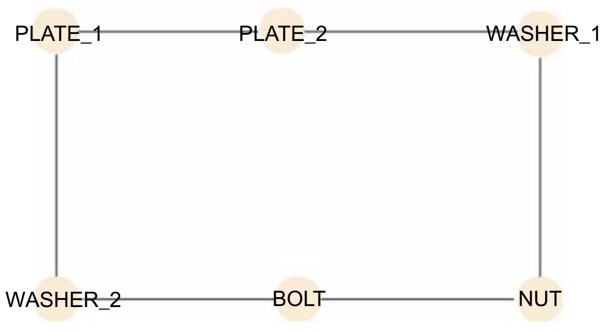
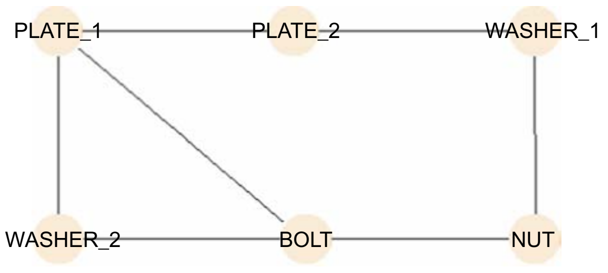


Figure 4 Liaison graph of bolt-nut plate fixing modified



CAD model assembly of a product is correctly made in relation to the real spatial position of each component and such a state is considered kinematically stable. So, each part will define its liaison for the mere fact that one or more of its surfaces are in contact (zero clearance) with the surfaces of other components (De Fazio and Whitney, 1987). This result is achieved by means of computer tools able to extract information of either contact or interference between components and, in an automatic way, to generate the liaison graph of the product assembly.

Automatic approach for assembly planning

The next step required to identify the assembly sequences of a product is devoted to find the sequences related to the defined liaison graph. Our approach is intended to identify possible sub-assemblies inside the liaison graph of the assembly through the evaluation of indices of importance for components and independent cycles or sub-assemblies. All the sub-assemblies will be arranged hierarchically and, for each one, a base node or platform element will be identified in order to generate its assembly sequences. Any sub-assembly will be considered as a new component and a new liaison graph will be created. So, the procedure will restart until no sub-assemblies or cycles will be identified.

Grouping of different components into sub-assemblies and definition of their sequences are done merely on the basis of the existence of the interactions. Others architectural or resource criteria have not been considered, such as manufacturability, orientation, personnel capabilities or product line strategy, from the moment that their involvement requires the participation of expert staff during the assembly sequences definition.

In this way, the complexity of the problem is reduced by means of the identification of independent sub-assemblies (Osorio Gómez and Viganò, 2010; Viganò and Osorio-Gomez, 2011). In fact, the assembly planning process based on sub-assemblies identification has been demonstrated as a viable tool in order to reduce the number of all possible sequences considerably decreasing the combinatorial problems encountered by other assembly planners working on large real world problems (Ong and Wong, 1999). Lee and Shin presented a methodology for assembly planning oriented to minimize the assembly cost and based on sub-assembly extraction decomposing an attributed liaison graph into a set of sub-graphs according to feasibility and difficulty of disassembly. To do this, the geometry of the part, physical

Table II Assembly sequences of bolt-nut plate fixing modified

No.	Assembly sequence						Feasibility
1	PLATE_1	BOLT	WASHER_2	NUT	WASHER_1	PLATE_2	No
2	BOLT	WASHER_2	PLATE_1	NUT	WASHER_1	PLATE_2	No
3	WASHER_2	PLATE_1	BOLT	NUT	WASHER_1	PLATE_2	No
4	PLATE_1	BOLT	WASHER_2	WASHER_1	PLATE_2	NUT	No
5	BOLT	WASHER_2	PLATE_1	WASHER_1	PLATE_2	NUT	No
6	WASHER_2	PLATE_1	BOLT	WASHER_1	PLATE_2	NUT	No
7	PLATE_1	BOLT	WASHER_2	PLATE_2	NUT	WASHER_1	No
8	BOLT	WASHER_2	PLATE_1	PLATE_2	NUT	WASHER_1	No
9	WASHER_2	PLATE_1	BOLT	PLATE_2	NUT	WASHER_1	No
10	PLATE_1	WASHER_2	BOLT	NUT	WASHER_1	PLATE_2	No
11	WASHER_2	BOLT	PLATE_1	NUT	WASHER_1	PLATE_2	No
12	BOLT	PLATE_1	WASHER_2	NUT	WASHER_1	PLATE_2	No
13	PLATE_1	WASHER_2	BOLT	WASHER_1	PLATE_2	NUT	No
14	WASHER_2	BOLT	PLATE_1	WASHER_1	PLATE_2	NUT	No
15	BOLT	PLATE_1	WASHER_2	WASHER_1	PLATE_2	NUT	No
16	PLATE_1	WASHER_2	BOLT	PLATE_2	NUT	WASHER_1	No
17	WASHER_2	BOLT	PLATE_1	PLATE_2	NUT	WASHER_1	No
18	BOLT	PLATE_1	WASHER_2	PLATE_2	NUT	WASHER_1	No
19	PLATE_1	BOLT	WASHER_2	NUT	PLATE_2	WASHER_1	No
20	BOLT	WASHER_2	PLATE_1	NUT	PLATE_2	WASHER_1	No
21	WASHER_2	PLATE_1	BOLT	NUT	PLATE_2	WASHER_1	No
22	PLATE_1	BOLT	WASHER_2	PLATE_2	WASHER_1	NUT	No
23	BOLT	WASHER_2	PLATE_1	PLATE_2	WASHER_1	NUT	Yes
24	WASHER_2	PLATE_1	BOLT	PLATE_2	WASHER_1	NUT	Yes
25	PLATE_1	BOLT	WASHER_2	WASHER_1	NUT	PLATE_2	No
26	BOLT	WASHER_2	PLATE_1	WASHER_1	NUT	PLATE_2	No
27	WASHER_2	PLATE_1	BOLT	WASHER_1	NUT	PLATE_2	No
28	PLATE_1	WASHER_2	BOLT	NUT	PLATE_2	WASHER_1	No
29	WASHER_2	BOLT	PLATE_1	NUT	PLATE_2	WASHER_1	No
30	BOLT	PLATE_1	WASHER_2	NUT	PLATE_2	WASHER_1	No
31	PLATE_1	WASHER_2	BOLT	PLATE_2	WASHER_1	NUT	Yes
32	WASHER_2	BOLT	PLATE_1	PLATE_2	WASHER_1	NUT	Yes
33	BOLT	PLATE_1	WASHER_2	PLATE_2	WASHER_1	NUT	No
34	PLATE_1	WASHER_2	BOLT	WASHER_1	NUT	PLATE_2	No
35	WASHER_2	BOLT	PLATE_1	WASHER_1	NUT	PLATE_2	No
36	BOLT	PLATE_1	WASHER_2	WASHER_1	NUT	PLATE_2	No

properties, the information of mating characteristics and tools is required in order to decide the feasibility of an assembly operation (Lee and Shin, 1990). The presented approach is very similar to Lee's methodology considering that possible sub-assemblies are identified through the definition of indices linked to the components and to the sub-assemblies themselves. A detailed flowchart from the product modelling to the automatic generation of assembly sequences is shown in Figure 5.

The automated proposed approach considers the following steps; where an example of a simple ball check-valve, with five components, has been used to better explain the method:

1 Analysis of the CAD product assembly model in order to detect either contacts between components represented by global clearances of zero value or interferences. The information is retrieved by means of a tool already included into the adopted CAD system, PTC – ProE/Wildfire (Figure 6). With such information both the adjacency matrix and the liaison graph of the assembly can be created (Figure 7). It is worth that the liason graph is not required for the identification of the assembly sequences but it is useful to understand the proposed approach.
2 Identification of graph nodes or components with degree value equal to one, if they exist. Grouping nodes with degree value equal to "one" with their adjacent nodes is considered the first step to identify independent sub-assemblies inside the liaison graph, which are the first steps in the assembly sequence. In the ball check-valve, there are not nodes with degree value equal to one.
3 Identification of induced cycles through a new combined algorithm of breadth-depth first search (Greenlaw, 1993). In graph theory, an induced cycle has no chords or straddling links. A chord or a straddling link is an edge joining two vertices of a cycle but is not itself an edge of the cycle (Gross and Yellen, 2006). The implemented algorithm explores all possible fundamental cycles travelling over an initial node. Every node is then progressively explored until no further nodes remain in the network. In the example under analysis, two induced

Figure 5 Flowchart from product modelling to generation of assembly sequences

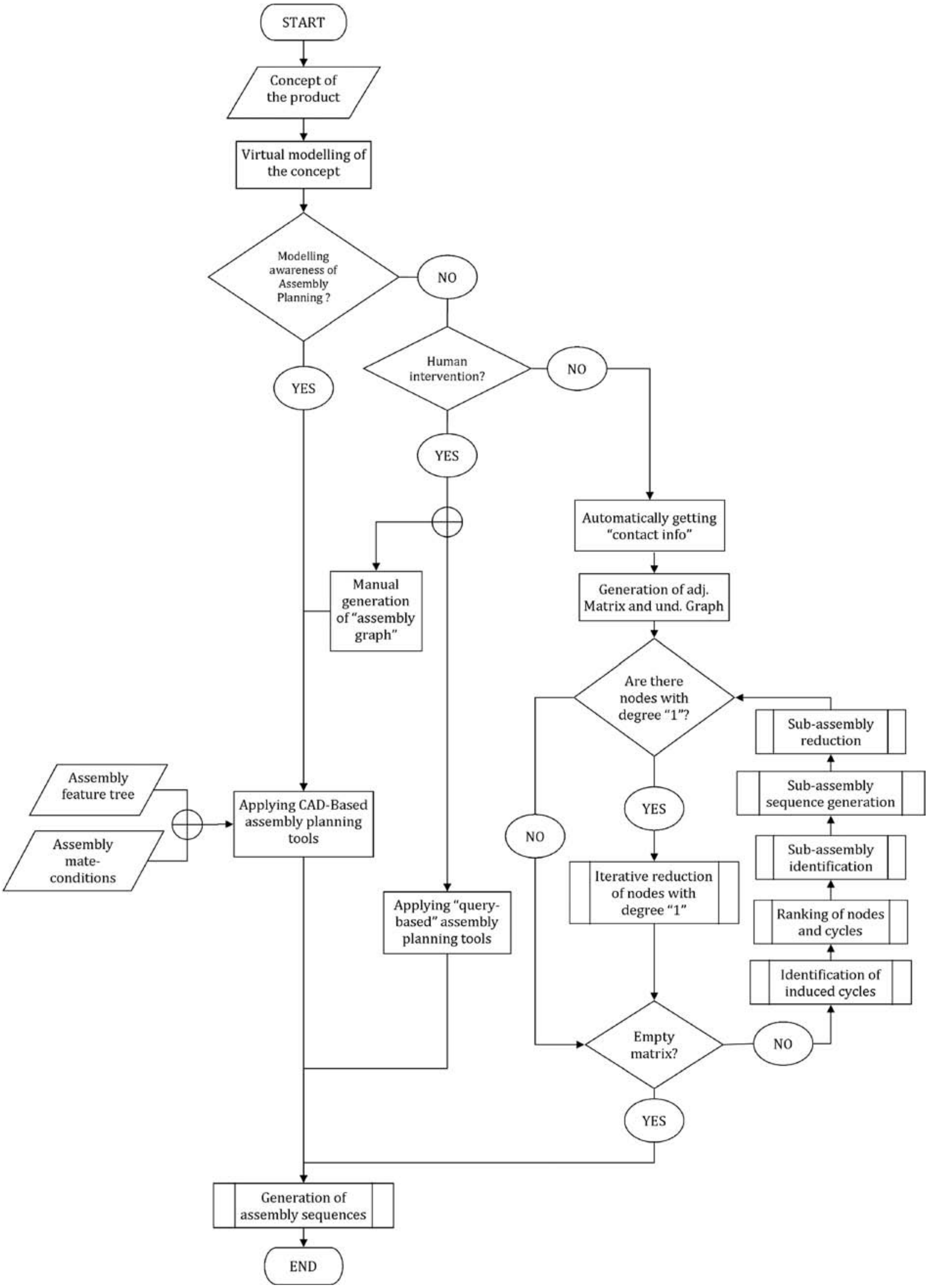


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Figure 6 Ball check-valve model

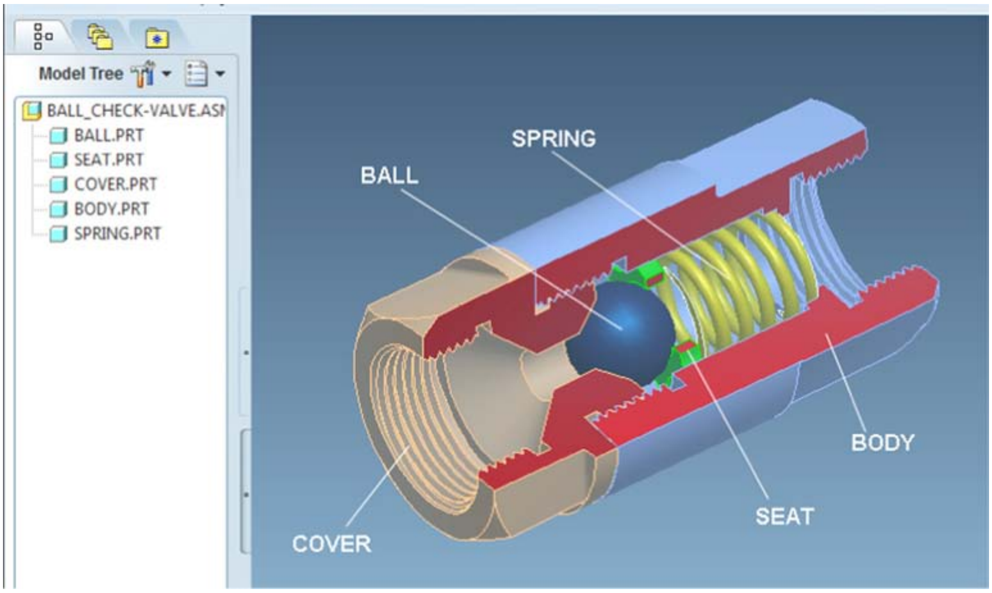
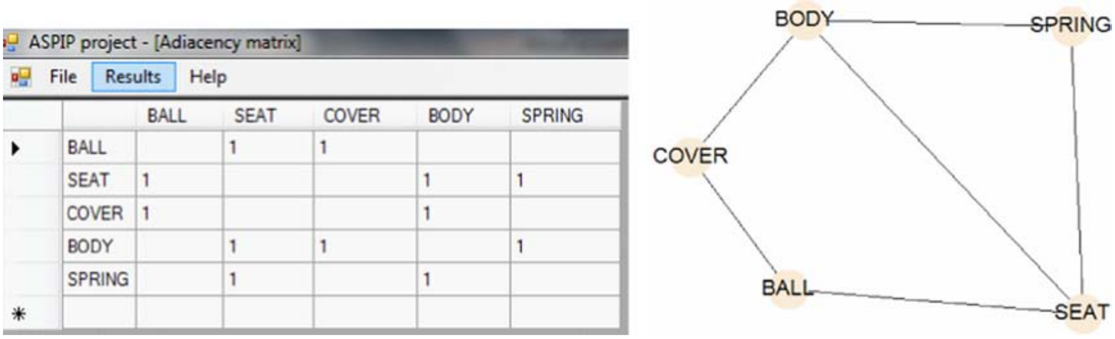


Figure 7 Adjacency matrix and connection graph for the ball check-valve model



	BALL	SEAT	COVER	BODY	SPRING
BALL		1	1		
SEAT	1			1	1
COVER	1			1	
BODY		1	1		1
SPRING		1		1	
*					

cycles have been identified after the first exploration: cycle 1 (ball-seat-body-cover) and cycle 2 (seat-body-spring).

4 Ranking of nodes based on the centrality index I_{CT}. The centrality condition of the ***i***-node helps to identify the components that must be assembled first than their corresponding neighbours, and it is defined by the next equation:

$$I_{CT_i} = \frac{w_{ND} \cdot I_{ND_i} + w_{PC} \cdot I_{PC_i} - w_{DAN} \cdot I_{DAN_i} - w_{CCF} \cdot I_{CCF_i}}{(w_{ND} + w_{PC} - w_{DAN} - w_{CCF})};$$

$$0 \leq I_{CT_i} \leq 1$$

where:

w_{ND} – weight for index of node degree.
I_{NDi} – index of i-node degree.
w_{PC} – weight for index of pertaining cycles.
I_{PCi} – index of pertaining cycles for the i-node.
w_{DAN} – weight for index of degree of adjacent nodes.
I_{DANi} – index of mean degree of adjacent nodes of the i-node.
w_{CCF} – weight for index of clustering coefficient.
I_{CCFi} – index of clustering for the i-node.

All indices are rated according to the number of nodes under analysis. The weight values applied to different indices have offered admissible results from heuristic analysis of different studied problems.

So, the centrality condition is calculated on the base of the different indices:

- Index of node degree, I_{ND}: the degree of a node (v_i) refers to its neighbouring nodes or to the number of edges that are connected to that node. In a system, the degree of a component indicates its importance.

  The index I_{ND} is the ratio between the degree of the i-node (v_i) and the sum of the degree for all nodes in the graph:

$$I_{ND_i} = \frac{d(v_i)}{\sum_{v_j \in V} d(v_j)}; \quad 0 \leq I_{ND_i} \leq 1$$

- Index of pertaining cycles, I_{PC}: all nodes (v_i) of the undirected connected graph with a degree value higher or equal than two belongs to at least to one induced cycle $c(v_i)$, of the set of cycles C. This is true if no vertices with degree value equal to one exist in the system. This index represents a value of interchangeability of that node, since a higher degree normally indicates a great participation in different induced cycles.

The pertaining ratio $PC(v_i)$ for a node (v_i) is defined by the relation between the number of pertaining cycles for that node $c(v_i)$ and the total number of cycles of the set C:

$$PC(v_i) = \frac{|c(v_i)|}{|C|};$$

By definition $c(v_i)$ indicates the induced cycles of the set C which contains the node $v(i)$ as one of their elements.

While the index of pertaining cycles I_{PC}, is the ratio of the pertaining ratio $PC(v_i)$ for the node v_i, to the sum of all values of PC for all the nodes of the set V, as indicated:

$$I_{PC_i} = \frac{PC(v_i)}{\sum_{v_j \in V} PC(v_j)}; \quad 0 \le I_{PC_i} \le 1$$

- Index of mean degree of adjacent nodes, I_{DAN}: this metrics represents the importance of the components connected to a defined element or sub-assembly into the system. It has been observed that a lower value of the mean degree of adjacent nodes is advantageous for the evaluation of the base components, and in this way, for the total centrality index of a node, the index I_{DAN} is negatively weighted.

  The mean degree of adjacent nodes or $\overline{DAN}(v_i)$ for the node (v_i) corresponds to the sum of degree of its neighbours divided by the number of neighbours:

  $$\overline{DAN}(v_i) = \frac{\sum_{v_i \in N(v_i)} d(v_i)}{d(v_i)}$$

  While the index I_{DAN}, is defined as the relation between the value of $\overline{DAN}(v_i)$ for the node (v_i) and the sum of the same value for all nodes of the set V:

  $$I_{DAN_i} = \frac{\overline{DAN}(v_i)}{\sum_{v_j \in V} \overline{DAN}(v_j)}; \quad 0 \le I_{DAN_i} \le 1$$

- Index of clustering, I_{CCF}: this index represents the degree of connection between the neighbours of a node v_i. The clustering coefficient of a node in a graph $G = (V,E)$ quantifies how close the node and its neighbours are of being a clique or a complete graph (Watts and Strogatz, 1998; Schank and Wagner, 2005). The clustering coefficient $CCF(v_i)$ for a vertex v_i is given by the ratio of links between the vertices within its neighbourhood $N(v_i)$ and the number of links that could possibly exist between them. Therefore, if a node v_i has k_i neighbours, ki(ki − 1)/2 edges could exist among the vertices within the neighbourhood.

  Thus, the clustering coefficient for undirected graphs can be defined as:

  $$CCF(v_i) = \frac{2.|\{e_{jk}\}|}{k_i(k_i - 1)}; \quad v_j, v_k \in N_i; e_{jk} \in E$$

This measure is equal to 1 if every neighbour connected to v_i is also connected to every other vertex within the neighbourhood and it is equal to 0 if no vertex that is connected to v_i connects to any other vertex that is connected to v_i.

Such a connectivity can be understood as modularity of such components. But, this index by itself does not make difference between components, so, a weighted clustering coefficient $WCCF(v_i)$ is defined as the degree of the vertex $d(v_i)$, multiplied by its corresponding clustering coefficient $CCF(v_i)$.

So, the I_{CCF} is defined by the ration between the weighted clustering coefficient $WCCF(v_i)$ of a node v_i and the sum of all the same coefficients for all nodes pertaining to the set of nodes V:

$$I_{CCF_i} = \frac{WCCF(v_i)}{\sum_{v_j \in V} WCCF(v_j)}; \quad 0 \le I_{CCF_i} \le 1$$

This metric indicates if an element is connected to a possible module.

It has been observed that a lower value of clustering of adjacent nodes is advantageous for base components evaluation, and in this way, for the total centrality index of a node, the index I_{CCF} is negatively weighted.

For the ball check-valve, Figure 8 shows the centrality node indices after the first cycle of analysis of the liaison graph indicating that the components "seat" and "body" have a higher value of $I_{CT(i)} = 0.3186$:

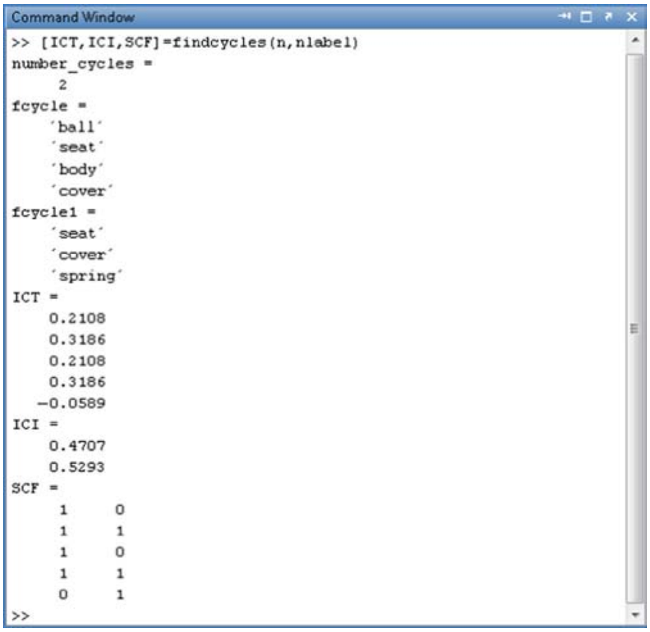
5. Ranking of cycles based on the importance indices I_{CI}. The importance of the ***i***-cycle evaluates the inner and outer positions of each cycle into the undirected graph, and its value is defined by the next equation:

$$I_{CI_i} = \frac{w_{CD} \cdot I_{CD_i} + w_{CC} \cdot I_{CC_i} + w_{NC} \cdot I_{NC_i}}{(w_{CD} + w_{CC} + w_{NC})}; \quad 0 \le I_{CI_i} \le 1$$

where:

w_{CD} – weight for index of cycle degree.
I_{CDi} – index of cycle degree.
w_{CC} – weight for index of cycle connectivity.

Figure 8 Indices for evaluation of nodes and induced cycles for the ball check-valve model



```
>> [ICT,ICI,SCF]=findcycles(n,nlabel)
number_cycles =
     2
fcycle =
    'ball'
    'seat'
    'body'
    'cover'
fcycle1 =
    'seat'
    'cover'
    'spring'
ICT =
    0.2108
    0.3186
    0.2108
    0.3186
   -0.0589
ICI =
    0.4707
    0.5293
SCF =
     1     0
     1     1
     1     0
     1     1
     0     1
>>
```

I_{CCi} – index of cycle connectivity.
w_{NC} – weight for index of component nodes centrality.
I_{NCi} – index of node centrality.

In the same way, as for index of nodes centrality, each index is weighted.

So, the importance of the cycle is based on the following indices:

- Index of cycle degree, I_{CD}: the degree of a cycle c_i with k components is the number of neighbouring nodes connected to all components of the cycle.Its value is defined as the ratio between the degree of the cycle c_i and the sum of all degrees for all induced cycles of the set C:

$$I_{CD_i} = \frac{d\left(c_i^k\right)}{\sum_{c_j^k \in C} d\left(C_j^k\right)}; \quad 0 \le I_{CD_i} \le 1$$

- Index of cycle connectivity, I_{CC}: the connectivity of a cycle $\mathrm{CC}\left(\mathrm{c}_\mathrm{i}^\mathrm{k}\right)$ for an induced cycle with k components is defined as the ratio between the number of neighbours and the number of nodes not belonging to that cycle:

$$CC\left(c_i^k\right) = \frac{d\left(c_i^k\right)}{|V| - k};$$

  So, the I_{CC} is defined by the ration between the connectivity of the cycle $CC\left(c_i^k\right)$ and the sum of the connectivity for all induced cycles:

$$I_{CC_i} = \frac{CC\left(c_i^k\right)}{\sum_{c_j^k \in C} CC\left(c_j^k\right)}; \quad 0 \le I_{CC_i} \le 1$$

- Index of node centrality, I_{NC}: the behaviour of the cycle respecting to its outer elements has been evaluated, in order to equally compare all cycles independently of their length k, as it follows:

$$\overline{NC}\left(c_i^k\right) = \frac{\sum_{v_j \in c_i^k} I_{CT}(v_j)}{k}$$

  Again, this value is rated for a cycle c_i considering the same value for all cycles of the set C. So, the index I_{NC}, is defined as:

$$I_{NC_i} = \frac{\overline{NC}\left(c_i^k\right)}{\sum_{c_j^k \in C} \overline{NC}\left(c_j^k\right)}; \quad 0 \le I_{NC_i} \le 1$$

  For the ball check-valve model, Figure 8 shows the importance cycle indices at the first step of analysis.

6. Sub-assembly identification. At this point the cycle with a higher value of importance index $I_{CI(i)}$ is selected as the initial sub-assembly and its node with greater value of centrality index $I_{CT(i)}$ is identified as the base node of the sequence. For the sub-assembly selected, $2^{(k-2)}$ sequences are generated. Where k is the length of the concerned cycle. If more than one node with the same value of $I_{CT(i)}$ exists, then as many possible sequences as platform nodes will be generated.

   For the ball check-valve model the cycle 2 (seat-body-spring) is the one with the bigger I_{CI}. Its first component of the sequence is the node with the bigger value of I_{CT}. The sequences start from nodes "seat" and "body" and $2{*}2^{(k-2)} = 2{*}2^{(3-2)} = 4$, four sequences are generated, as it is presented in Table III.
7. Sub-assembly reduction. The assembly sequences for the identified sub-assembly have been generated and the included components have been reduced to the base node. In the ball check-valve the cycle 2 (seat-body-spring) is reduced to the sub-assembly SA1 and finally one induced cycle remains, that is (cover-ball-SA1).
8. Return to the second step and repeat previous steps until the last remaining cycle is analysed and reduced. At this point, each node of the cycle is considered as a possible base component and sequences are generated for each one. In the ball check-valve, there are three base nodes and, $3{*}2^{(k-2)} = 2{*}2^{(3-2)} = 6$, six sequences are generated, as it is shown in Table IV.

At the end of the explained procedure the list of possible assembly sequences is obtained.

The total number of the possible assembly sequences corresponds to the multiplication among the number of the sequences found for each step. For the case analysed, the solution presents, $4{*}6 = 24$, 24 different possible assembly sequences which are presented in Table V. These solutions are equivalent from a topological point of view and a manufacturer can filter those using technical parameters of the current assembly line, identifying preferred precedence relations or through implementation of virtual tools intended to visual evaluation.

In order to obtain feasible solutions during the implementation of the automated approach it is possible to perform a feasibility analysis through a query-based procedure at the end of the process for each of the final solutions. This query-answer process must be executed observing the order of the steps, since if an unfeasible sub-assembly is identified; the mechanical system should be reviewed.

For the ball check-valve, the feasibility of each sequence for sub-assembly 1 (SA1) is reviewed in Table VI and there are only two feasible sequences and together with the six

Table III Sequences generated for the cycle 2 of the ball check-valve model

Base node	Sequence
Seat	Seat < body < spring
	Seat < spring < body
Body	Body < spring < seat
	Body < seat < spring

Table IV Sequences generated for the last induced cycle of the ball check-valve model

Base node	Sequence
Cover	Cover < ball < SA1
	Cover < SA1 < ball
Ball	Ball < cover < SA1
	Ball < SA1 < cover
SA1	SA1 < ball < cover
	SA1 < cover < ball

Table V All sequences generated for the whole assembly in the ball check-valve model

Base node	Sub-sequence	Sequence
Cover	Cover < ball < SA1	1 Cover < ball < seat < body < spring
		2 Cover < ball < seat < spring < body
		3 Cover < ball < body < spring < seat
		4 Cover < ball < body < seat < spring
	Cover < SA1 < ball	5 Cover < seat < body < spring < ball
		6 Cover < seat < spring < body < ball
		7 Cover < body < spring < seat < ball
		8 Cover < body < seat < spring < ball
Ball	Ball < cover < SA1	9 Ball < cover < seat < body < spring
		10 Ball < cover < seat < spring < body
		11 Ball < cover < body < spring < seat
		12 Ball < cover < body < seat < spring
	Ball < SA1 < cover	13 Ball < seat < body < spring < cover
		14 Ball < seat < spring < body < cover
		15 Ball < body < spring < seat < cover
		16 Ball < body < seat < spring < cover
SA1	SA1 < ball < cover	17 Seat < body < spring < ball < cover
		18 Seat < spring < body < ball < cover
		19 Body < spring < seat < ball < cover
		20 Body < seat < spring < ball < cover
	SA1 < cover < ball	21 Seat < body < spring < cover < ball
		22 Seat < spring < body < cover < ball
		23 Body < spring < seat < cover < ball
		24 Body < seat < spring < cover < ball

sequences for the final cycle, there are 12 sequences which feasibility would be analysed in Table VII, where, at the end, there are only five feasible sequences for the assembly.

Case study

A case study, taken from the bibliography, is presented in order to evaluate the approach and to compare the final results with reliable information. The selected case study, named "assembly from industry", has been presented by De Fazio and Whitney. The assembly has a geometry sufficiently represented by circular symmetry about the axial centreline and, to simplify the problem, no fasteners were considered into the assembly. So, there are only 11 parts assembled, identified with the alphabetical letters from A to L (Figure 9) (De Fazio and Whitney, 1987). This example has also been selected considering its conceptual level of the model, in line with the assumption that a concept model of an assembly is enough to automatically define a list of assembly sequences, where at least there is a feasible solution.

Table VI Feasibility analysis for the cycle 2 of the ball check-valve model

Base node	Sequence	Feasible?
Seat	Seat < body < spring	No
	Seat < spring < body	Yes
Body	Body < spring < seat	Yes
	Body < seat < spring	No

Based on the previous assumptions, the approach considers the following results:

- A conceptual CAD product assembly is modelled and the information of contacts and interferences is retrieved with the CAD system. The liaison graph of the assembly has been created (Figure 10).
- Grouping nodes with unitary degree value the component F has been joined to the component E forming the first sub-assembly.
- 13 induced cycles have been identified after the first exploration (Table VIII).
- The centrality node indices were calculated (Table IX).
- The importance cycle indices were calculated (Table X).
- With the indices, the next independent sub-assembly identified, according to Table X, includes components A-C-B-G, and according to Table IX, the component A is identified as the base node.
- After the first sub-assembly reduction, iteration until the last remaining cycle is analysed. Table XI shows all sub-assemblies found during each step of the procedure.

The automatic solution presents $(1 \times 4 \times 2 \times 2 \times 6) = 96$ different possible feasible and unfeasible assembly sequences. In this case study, the proposed approach offers better results in contrast with the 36 queries and the 40 possible assembly sequences obtained by the application of De Fazio and Whitney's (1987) method.

Anyway, in the same way, as with the De Fazio and Whitney's approach, the number of assembly sequences can be reduced, with expert staff intervention, evaluating the feasibility of each assembly sequence, that is in this case, answering to $(1 + 4 + 2 + 2 + 6) = 15$ queries as reported in the last column of Table XI. Here, $(1 \times 1 \times 1 \times 1 \times 4) = 4$ different feasible assembly sequences are finally obtained. The number is reduced to four sequences answering to 15 queries corresponding to possible feasible assembly sequences for the sub-assembly groups identified. De Fazio and Whitney have further reduced the 440 assembly paths to 16 solutions under two additional constraints, but always considering the expertise of the manufacturer and some well-defined manufacturing conditions.

In brief, this approach allows automatically obtaining a lower number of possible assembly sequences respecting to theoretical approaches based on querying and answering techniques, and through an alternative once-off query-based analysis it is possible to reduce the number of solutions to a small list of feasible assembly sequences.

Conclusions

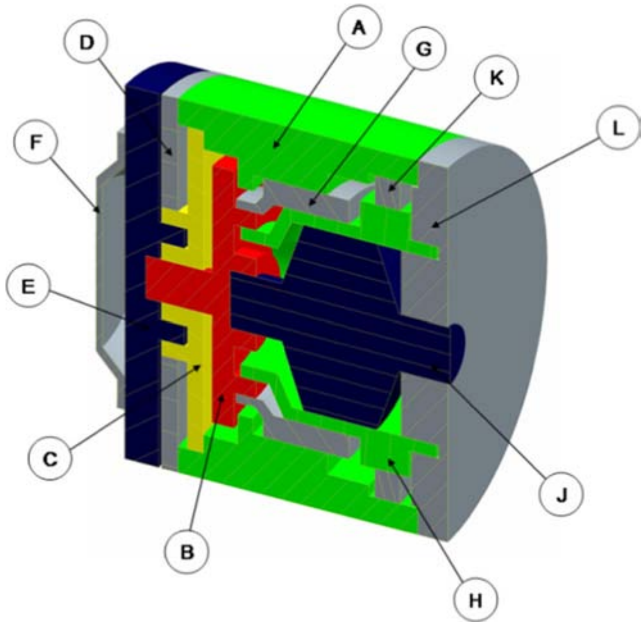
The approach allows skilled and unskilled staff to automatically obtain at least one feasible assembly exploratory plan for physical discrete products based on contact information extracted from 3D-CAD assembly models even at the early stages of the design process. Besides, this approach is independent of the modelling technique and no assembly-based considerations should be included in the modelling stage. Anyway, it would be conceivable analyse the 3D model to select some specific components, such as parts which are inherent to the assembly of others, that could be neglected or grouped so to reduce the number of the solutions.

The hierarchical approach identifying independent sub-assemblies allows an objective evaluation of the

Table VII Feasibility analysis for all the sequences of the ball check-valve model

Base node	Sub-sequence	Sequence	Feasible?
Cover	Cover < ball < SA1	1 Cover < ball < seat < spring < body	Yes
		2 Cover < ball < body < spring < seat	No
	Cover < SA1 < ball	3 Cover < seat < spring < body < ball	No
		4 Cover < body < spring < seat < ball	No
Ball	Ball < cover < SA1	5 Ball < cover < seat < spring < body	Yes
		6 Ball < cover < body < spring < seat	No
	Ball < SA1 < cover	7 Ball < seat < spring < body < cover	Yes
		8 Ball < body < spring < seat < cover	No
SA1	SA1 < ball < cover	9 Seat < spring < body < ball < cover	Yes
		10 Body < spring < seat < ball < cover	Yes
	SA1 < cover < ball	11 Seat < spring < body < cover < ball	No
		12 Body < spring < seat < cover < ball	No

Figure 9 Representation in a 3D model of the trucks transmission proposed by De Fazio and Whitney (1987), simplified generation of all mechanical assembly sequences



importance of components and their connections through comparison indices evaluated according to graph-based theories.

This process is different from conventional methodologies for ASA seeing that neither questions intended to precedence establishment are formulated to the staff nor assembly expert intervention is required. Also, it does not pursue only feasible sequences, but without precedence questions it is automatically reduced the number of obtained sequences guaranteeing the presence of a feasible one among those derived from the process.

After the application of this automatic approach, with a further analysis where the human intervention is required, it is possible to reduce the initial number of solutions and to remove the unfeasible ones. If no feasible solution is obtained, the product should be controlled in order to identify instability or over constrained conditions.

Figure 10 Liaison graph of the trucks transmission

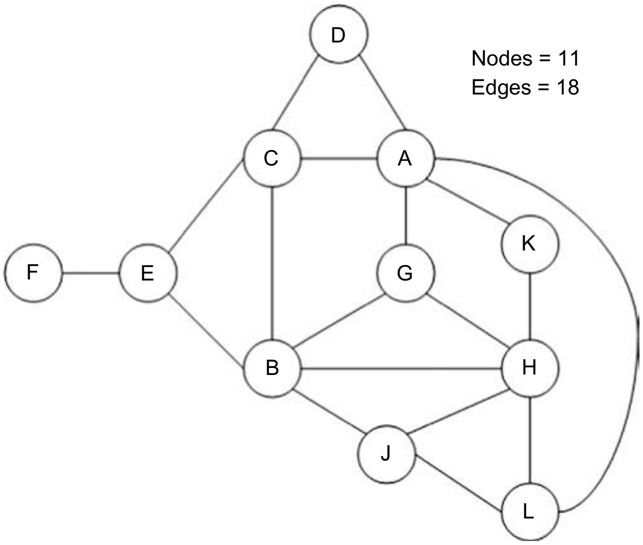


Table VIII Induced cycles of the liaison graph of the trucks transmission

No.	Cycles				
1	A	C	D		
2	A	C	B	G	
3	A	G	K	H	
4	A	K	H	L	
5	A	G	H	L	
6	A	K	H	B	C
7	A	C	B	H	L
8	A	C	B	J	L
9	A	G	B	J	L
10	B	G	H		
11	B	H	J		
12	J	H	L		
13	E	C	B		

Table IX Indices for nodes evaluation, sub-assembly identification and sequence definition

Index	Node	Node degree	I_{ND}	Pertaining cycles	Rate of pertaining cycles	I_{PC}	$\sum$ degree adj. nodes	Mean degree adj. nodes	I_{DAN}	Clustering coefficient CCF	Weighted CCF	I_{CCF}	Centrality I_{CT}
1	"J"	3	0.088	4	0.308	0.078	13	4.333	0.107	0.667	2.000	0.156	0.035
2	"B"	5	0.147	8	0.615	0.157	17	3.400	0.084	0.300	1.500	0.117	0.204
3	"H"	5	0.147	8	0.615	0.157	16	3.200	0.079	0.300	1.500	0.117	0.206
4	"G"	3	0.088	5	0.385	0.098	15	5.000	0.123	0.333	1.000	0.078	0.086
5	"C"	4	0.118	6	0.462	0.118	14	3.500	0.086	0.333	1.333	0.104	0.140
6	"D"	2	0.059	1	0.077	0.020	9	4.500	0.111	1.000	2.000	0.156	−0.055
7	"E"	2	0.059	1	0.077	0.020	9	4.500	0.111	1.000	2.000	0.156	−0.055
8	"A"	5	0.147	9	0.692	0.176	14	2.800	0.069	0.100	0.500	0.039	0.270
9	"K"	2	0.059	3	0.231	0.059	10	5.000	0.123	0.000	0.000	0.000	0.056
10	"L"	3	0.088	6	0.462	0.118	13	4.333	0.107	0.333	1.000	0.078	0.114

Table X Indices for sub-assembly evaluation

	Cycle	Cycle degree	I_{CD}	$\sum$ nodes centrality	Mean nodes centrality	I_{NC}	Cycle connectivity	I_{CC}	Importance I_{CI}
1	*A* C D	5	0.0758	0.3548	0.1183	0.0603	0.7143	0.0645	0.0669
2	A C B G	6	0.0909	0.6990	0.1748	0.0891	?0000	0.0903	0.0901
3	A G K H	5	0.0758	0.6173	0.1543	0.0787	0.8333	0.0753	0.0766
4	A K H L	5	0.0758	0.6451	0.1613	0.0822	0.8333	0.0753	0.0778
5	A G H L	5	0.0758	0.6748	0.1687	0.0860	0.8333	0.0753	0.0790
6	A K H B C	5	0.0758	0.8754	0.1751	0.0893	?0000	0.0903	0.0851
7	A C B H L	5	0.0758	0.9329	0.1866	0.0951	?0000	0.0903	0.0871
8	A C B J L	5	0.0758	0.7622	0.1524	0.0777	?0000	0.0903	0.0813
9	A G B J L	5	0.0758	0.7076	0.1415	0.0722	?0000	0.0903	0.0794
10	B G H	6	0.0909	0.4953	0.1651	0.0842	0.8571	0.0774	0.0842
11	B H J	5	0.0758	0.4449	0.1483	0.0756	0.7143	0.0645	0.0720
12	J H L	4	0.0606	0.3549	0.1183	0.0603	0.5714	0.0516	0.0575
13	E C B	5	0.0758	0.2888	0.0963	0.0491	0.7143	0.0645	0.0631

Table XI Assembly sequences for the trucks transmission example

				Possible assembly sequences		
Step	**Sub-assembly components**	**Sub-assembly code**	**Qty**	**Precedence**	**Assembly sequence code**	**Feasible**
1	E-F	E'	1	$E < F$	$E'(1)$	Yes
2	A-C-B-G	A'	4	$A < C < B < G$	$A'(1)$	No
				$A < G < B < C$	$A'(2)$	Yes
				$A < C < G < B$	$A'(3)$	No
				$A < G < C < B$	$A'(4)$	No
3	H-L-J	H'	2	$H < L < J$	$H'(1)$	No
				$H < J < L$	$H'(2)$	Yes
4	A'-D-E'	A''	2	$A' < D < E'$	$A''(1)$	Yes
				$A' < E' < D$	$A''(2)$	No
5	A''-K-H'	FS	6	$A'' < K < H'$	FS(1)	Yes
				$A'' < H' < K$	FS(2)	No
				$K < A'' < H'$	FS(3)	Yes
				$K < H' < A''$	FS(4)	Yes
				$H' < K < A''$	FS(5)	Yes
				$H' < A'' < K$	FS(6)	No

It is expected that such a proposed approach opens a possibility for better integration of assembly planning topics into the early stages of design as well as opens the possibility to the product assembly analysis by means of product data management (PDM) or product life-cycle management (PLM) systems. For example, the extraction of the adjacency matrix could be realised not opening the CAD system, but using an application directly connected with the PDM/PLM database. Besides, many research studies are devoted to analyse the possibility of using some data of the product directly from that database in order to allow the management to take some decision about the product under development. The product maturity assessment analysis is a field where such an approach could be used.

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Corresponding author

Roberto Viganò can be contacted at: roberto.vigano@polimi.it