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Automatic assembly sequence exploration without precedence definition

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Abstract Today the assembly sequence for the products is often carried out manually and its definition, typically, is very expensive, not guaranteeing optimal solutions. Coming up with an efficient assembly sequence is the essential step to improve process productivity and reduces the time and costs related to assembly machines and equipment. The issue related to the assembly sequence of a product depends on the total number of the its components. In particular, the number of the possible sequences can be obtained through the calculus of the factorial of the number of the product components. This work presents an automatic approach intended to define assembly sequences, based on the information regard the contacts and the interferences existing among the components, which is obtained by the assembly CAD model of the product. The level of the information required by this approach allows its implementation at early stages of design, as soon as the layout of the conceptual solution of the product is defined, independently by the method used to model the CAD assembly. The procedure proposed is focused to obtain a reduced number of assembly sequences, guaranteeing that there is at least one feasible assembly sequence among them. The procedure is oriented to iteratively identify independent and important subassemblies into the CAD assembly, then merge them to specific assembling nodes and generate sequences until the whole product is analyzed. After a brief review of current methodologies developed for assembly planning, in this paper, the automated procedure for assembly sequence generation is explained and applied on an example, obtaining feasible solutions.

Keywords Assembly sequence analysis · Automatic assembly sequences definition · Computer aided assembly planning · Design for assembly

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1 Introduction

The processes of product design and development are leading to the reduction of the development time and of the costs through integration of different industrial expertise areas and the full exploiting of the informatics tools for the aided design and the information management. This trend, devoted to the evaluation of the functions, architecture and high level information of the product, is today required, as far as possible, already at the early stages of design. The aim is to allow the designer to compare different solutions, rather than focusing on a single version of the product, whose later development could implicate undesired modifications during the last steps of the design process.

One of these evaluations is devoted to the planning of the assembling of the product that it normally takes place at the final stages of the design process, when the specialized technical staff, according to experience and specific requirements of the assembly line, defines the optimal assembly sequence. Define an efficient assembly sequence is essential to improve the production process and to reduce the times and the costs related to the assembly phase, including those of the machines and of the equipment [1].

Anyway, researches on the assembly field have developed approaches oriented to define all the feasible assembly sequences, generally, making use of CAD software systems, in order to detect geometrical interferences and to analyse the possible relative movement among the parts, so as to define the precedence between them [2]. The implementation of these approaches is expensive, time consuming and it is very difficult to implement into a collaborative working environment at early stages of the design process since they are based on specific technical know-how. Also, they require a detailed level of product information and their suitability has not been proved at industrial level.

This work presents, through the analysis of the current theories and coherently with the product design process, the development of an automatic approach intended to define assembly sequences, based on the information regard the contacts and the interferences existing among the components, which is obtained by the assembly CAD model of the product. The level of the information required by this approach allows its implementation at early stages of design, as soon as the layout of the conceptual solution of the product is defined, independently by the method used to model the CAD assembly. The procedure proposed is focused to obtain a reduced number of assembly sequences, guaranteeing that there is at least one feasible assembly sequence among them. The procedure is oriented to iteratively identify independent and important subassemblies into the CAD assembly, then merge them to specific assembling nodes and generate sequences until the whole product is analysed.

The next section presents some aspects about the theory and the development of the assembly sequence planning and the virtual modelling tasks in order to establish the research bases for the proposed automatic approach, which is presented further along. Finally, a practical case study is carefully explained in order to permit a better understand of the functionality of the approach and to present some important considerations about its application according to the nature of the product. In a like manner, the efficiency of the approach is compared with a well-known theoretical example.

2 Assembly sequence planning

The assembly task of a product has been studied as an independent factor in the life-cycle of the product, but when the demands related to the cost, to the time and to the quality have become more stringent, and the whole product development process has presented the necessity to be shortened, the industry has tried to combine all the design process tasks into a single phase. This has led to the born of different approaches, called: Design for Manufacture (DfM), Design for Assembly (DfA), Design for Variety (DfV), Design for Quality (DfQ), Design for Reliability (DfR), Design for Disassembly (DfD), Design for Maintainability (DfMa), and so on [3]. The Design for Assembly (DfA) is mainly oriented to redesign the product with the aim to minimization of both the costs and the time of the assembly tasks, following the guidelines targeted to the reducing the number of components, ensuring the ability to be assembled together. The DfX methods do not consider combinatorial aspects related to the choice of the assembly sequence, which is, instead, the target of the approach called Assembly Sequence Planning (ASP) or Assembly Sequence Analysis (ASA) [4]. This approach is focused on the definition of the feasible assembly sequences for a product with a defined architecture. It depends on the information and knowledge available for the product and its assembly process and it is useful for the study of very complex systems. Such as in the Computer Aided Assembly Planning (CAAP) methods, the information related to the assembly relationships and the constraints among the parts (co-planarity, coaxiality, mating, orientation, etc.), defined during the modelling step, can be retrieved from 3D CAD models.

Most of the current developed methodologies for the assembly sequence planning are based on queries involving skilled staff. Doing so, the generation of the assembling feasible sequences relies on the identification of technical rules or relationships of precedence among the parts, which are defined by the experts, knowing the layout of the product [5,6]. Some approaches start from a well-defined product architecture, like the methods suggested by Bourjault [7] and De Fazio and Whitney [8], and are applicable without the use of a 3D CAD model. While CAD-based approaches, as those proposed by Gottipolu [9] and Lin [10], require a previous knowledge of the assembly sequence and/or proper definition of the assembly constraints. In any case, the product layout must be known and visible and the experts' intervention is essential from the first steps of implementation of the methods.

Many of these methods may not be practicable at industrial level because of the long time needed for the repetitive inquiries required, as well as of the great number of solutions generated.

3 Virtual modelling considerations

The issue related to the assembly sequence of a product depends on the total number of the its components. Mathematical considerations ensure that the extraction of the product assembly sequences may be obtained through a combinatorial approach. In particular, without any other information, the number of the possible sequences can be obtained through the calculus of the factorial of the number of the product components. Anyway, the authors argue that further reduction of the number of the possible feasible assembly sequences can be directly derived by an automatic extraction of information from the CAD model [11].

Due to the nature of CAD systems and of the procedures currently used in the creation of the 3D assembly models, it is very difficult to establish the assembly precedence, between two components, based on either the assembly relationships or by the constraints entered by the user. Here it is worth

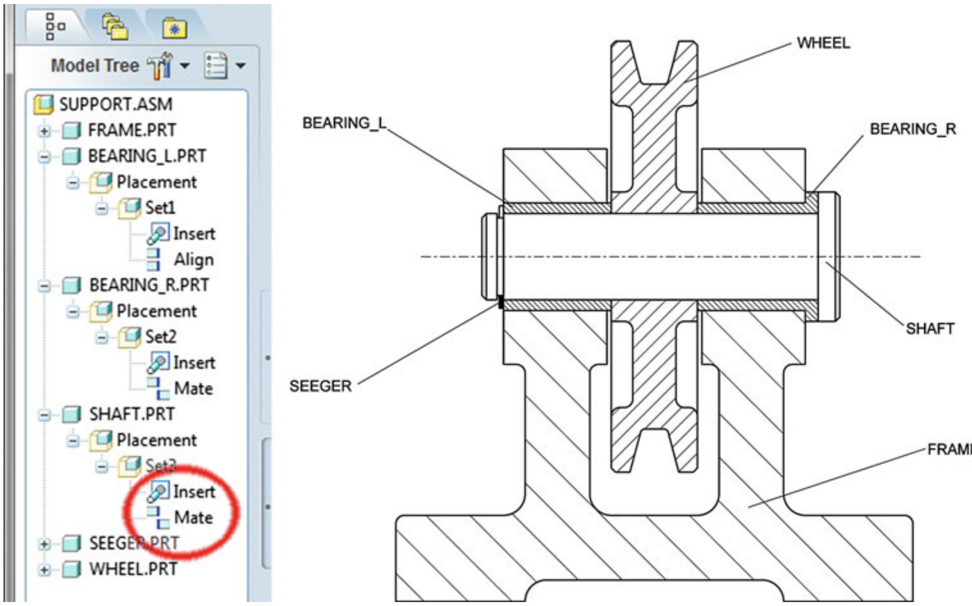

Fig. 1 Pulley-support assembly with model tree

observing that, into the modern feature-based CAD systems, the modelling task of an assembly could be conducted in different ways. For example, the assembly model could be done placing the parts according to a specific assembly sequence or, conversely, they could be placed without a pre-defined order. At least in the first case a sequence of the product assembly is provided, but may not necessarily be the best.

In both cases, the position of the single part becomes completely defined when the part itself is full constrained with respect to the other related parts in the 3D assembly. It is, also, easy to prove that the type of constraints, offered by the 3D CAD systems, leads to a relationships system other than those obtained in the real assembly. This brings to the condition that the single part of the assembly is fixed, by the CAD point of view, before that all the real constraints are imposed.

Hence, the CAD model requires the definition of a lower number of assembly relationships respecting to those required by the product in the reality.

This lower number of constraints present in the CAD assembly does not allow to define the assembly sequence in automatic manner.

For example, the assembly conditions for the model of the pulley-support shown in Fig. 1, defined by the CAD user, permit the creation of the graph reported in Fig. 2, while the real graph, useful for the assembly sequence definition, is shown in Fig. 3. This is due to the fact that the shaft is completely constrained when it is related to the right bearing by means of the "insert" and the "mate" assembly relationships (Fig. 1), and, in this way, the link with the left bearing is not required for the purpose of the CAD modelling. Same considerations could be made for the link between the wheel and the left bearing.

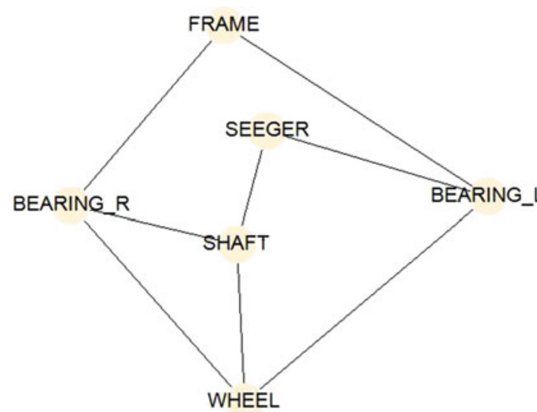

Fig. 2 Liaison graph for pulley-support assembly derived from CAD model (incomplete)

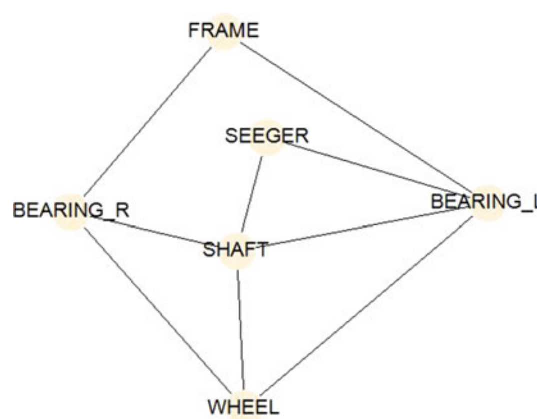

Fig. 3 Liaison graph for pulley-support assembly with correct links among the parts

In this way it is very difficult to obtain a reliable liaison graph, useful for further development of feasible assembly sequences, through the analysis of standard assembly relationships, even though the designer is able to assembly the different parts in a correct order into the CAD model.

Same considerations can be done with regards to the usage of the top-down paradigm during the CAD modelling and assembly. This modelling method uses a reference sketch, also called skeleton, to build the single parts directly in the assembly environment. So, no mating connection can be extracted from the assembly, and no graph, based on assembly constrains, can be realised.

Independently of the chosen modelling CAD technique, in order to capture design intent, different attempts for assembly relationships definition at conceptual stage have been proposed from many researchers. One of these is based on the definition of the assembly formalisms and/or using an assembly abstract representation where the relative position of each part is described specifying its relationship with the other components [12–14]. Another relies on the systematic methodology for assembly design proposed by Whitney [15], where a kinematic constraint structure and a systematic scheme, by which the parts are located in the space in relative mode to each other, are defined. All of this followed by the declaration of assembly features that connect parts in such a way to create the desired constraint relationships. However, in both theories, the definition of the relationships between the parts is still a designer's job.

Arun and Rao [16], to facilitate assembly analysis and planning, proposed an API for a CAD software to extract assembly related data (links and relationships between the assembled parts and the involved features), to replace the human interpretation of the assembly design. But, anyway, also in this proposed method, the assembly sequence is not automatically generated.

Wang et al. [17] state that "most of CAD tools currently do not have the capability to directly analyse the feasibility of a given assembly plan for a product or to generate an optimal or near-optimal assembly plan", and so, human intervention is required.

Su [18] presented an integrated software prototype system to find out the geometric assembly precedence relations based on the assembly CAD model and to automatically infer feasible assembly sequences applying an optimization algorithm; but the interaction human–computer is required to analyse the assembly conditions existing between each pair of components.

Neelamkavil [19] proposed a matrix-based analysis in order to identify sub-assemblies and possible sequences from a detailed CAD assembly, but the matrices are compiled manually and the sub-assemblies are identified by the user and do not automatically extracted by the system.

In conclusion, most of previous researches related to computer tools require some human interaction and depend on the modelling technique used to obtain specific information for their corroboration, again.

4 Research bases

The authors consider that better results could be obtained considering only the spatial interactions between the parts and neglecting both the relationships and constraints made by the user during the realization of the 3D CAD model.

So, by means of computer tools directly connected with the CAD database, it is possible to automatically extract information of contact and interference between components able to be used for the generation of topological information matrices and/or graphs. From this information is possible to identify independent subassemblies and reduce the problem complexity.

In fact, the assembly planning process based on sub-assemblies identification has demonstrated its suitability to reduce the number of all possible sequences, decreasing considerably the problems encountered on the real world combinatorial problems [20]. Lee and Shin have presented a methodology for assembly planning directed to minimize the assembly cost, based on the extraction of subassemblies by means of the breakdown of a liaison graph according to the feasibility and difficulty of disassembly. To do this, the parts geometry, their physical properties and the information concerning the mating characteristics and the assembly tools, are required. Everything in order to decide the feasibility of an assembly operation [21]. The automatic approach presented here is similar to the Lee's methodology seeing that the identification of possible sub-assemblies, with their own sequences, is realised through the definition of indices, related to the nodes and to the sub-assemblies, derived from a process of analysis about experimental data and their validation.

Besides, the proposed automatic approach is able to obtain specific information for assembly sequence definition regardless of the adopted modelling technique and of the definition of detailed information only available at later stages of design [11].

In the next paragraphs and after brief considerations upon the assembly modelling, the automated procedure proposed for assembly sequence generation is explained and applied on an example case.

5 Proposed assembly planning approach

The production process of a product is frequently defined during the detail design stage, when all the technical aspects of the product are already known. The product layout, with the geometrical information useful for the analysis of the assembly sequences, can also be obtained between the conceptual design phase and the embodiment design phase. This layout contains qualitative information related to the disposition of the components of the product, as such as the topologic data, which seldom change when the quantitative data, i.e. dimensions, tolerances, etc., are defined during the detail design stage. According to the last statement, it is hence possible to analyse the feasible assembly sequences already from the early stages of the design process.

So, it is possible to define a process able to generate a finite number of assembly sequences, including at least one feasible solution, starting from the product information generated at early stages of the design and without human intervention.

This automatic method is intended to identify the subassemblies included into the product and arrange them in hierarchical manner till completion of the whole assembly sequence. This goal is obtained considering, for each subassembly, a node or a platform element as a base for the generation of the internal sequences of the assembly. When the identified subassemblies have been mounted, they are considered as a single part into the system under analysis and, in this way the procedure starts again in order to find new subassemblies, and so on, until the whole product is assembled.

Grouping of different components into subassemblies and the definition of their assembly sequences are done merely on the basis of the existent interactions in the CAD model of the product. In this method only the contacts and the interferences among the surfaces of the parts of the 3D model have been considered. No other criteria such as the facility to manipulate the parts or their reciprocal orientation into the product have been considered, since the implication of such architectural and geometrical aspects requires the collaboration of expert staff for the extraction of the assembly sequences of the product under study.

In brief, this approach is based on subassembly identification and grading of nodes and subassemblies through different indices related to contacts between components and their importance.

6 Case study

The proposed approach has been tuned through testing with several different products, considering different modelling techniques, the component interactions and the design aspects.

In order to better explain the proposed approach, a case study related to a clamp is presented. The CAD model of the clamp has been downloaded from a web library of holding products and it has been processed in order to demonstrate that the approach is able to extract at least a feasible assembly sequence. The check, about the assembly sequences obtained, will be made through the human intervention. The model has been downloaded in the native CAD file format to conserve the original modelling technique and the design intent, also to demonstrate how this approach is independent of these aspects. Only the name of the different components has been changed for better understanding. The product model is composed of fifteen (15) components as a whole, as it is shown in Fig. 4.

The proposed approach is developed in the following steps:

1. STEP 0 Identification of contacts or interferences among components from the 3D-CAD assembly model, where all components are located in a stable position for the final assembly state, independently of possible further movements and contacts in operation. As stated by De Fazio and Whitney [8] the contact relationship between components include force fits, threaded fits, adhesion, compression contact, and even contact by virtue of a part resting on another part.
   With such information it is possible to generate the square symmetric binary adjacency matrix for the whole assembly system (Fig. 5a). As well, the undirected graph (Fig. 5b) showing the interaction between parts.
2. STEP 1 The automatic analysis starts with the identification and the reduction of the nodes that have connection degree value equal to one ($dv_i = 1$, with dv_i as the degree of the node v_i). This because those components interacting with only one of the other components and, when they are identified, their assembly operation is considered as the first of the possible subassemblies for the assembly sequence.
   In this case, the "knob (K)" and the "stopper (ST)" parts could be assembled to the "lever 2 (L2)" and to the "screw (SC)" components respectively, producing subassemblies "L2*" and "SC*". So, in the first step we have two possible subassemblies, considering that the component with higher connection degree is the base of the subassembly, and the assembly graph is reduced to thirteen (13) components, as it is shown in the Fig. 6.
3. STEP 2 Next, a new developed algorithm to identify the induced cycles or possible subassemblies is applied. 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. The algorithm applied in this step is based on a combined algorithm of Breadth-Depth First Search [22] and explores first all possible fundamental cycles travelling over an initial node and then removes that node from the given

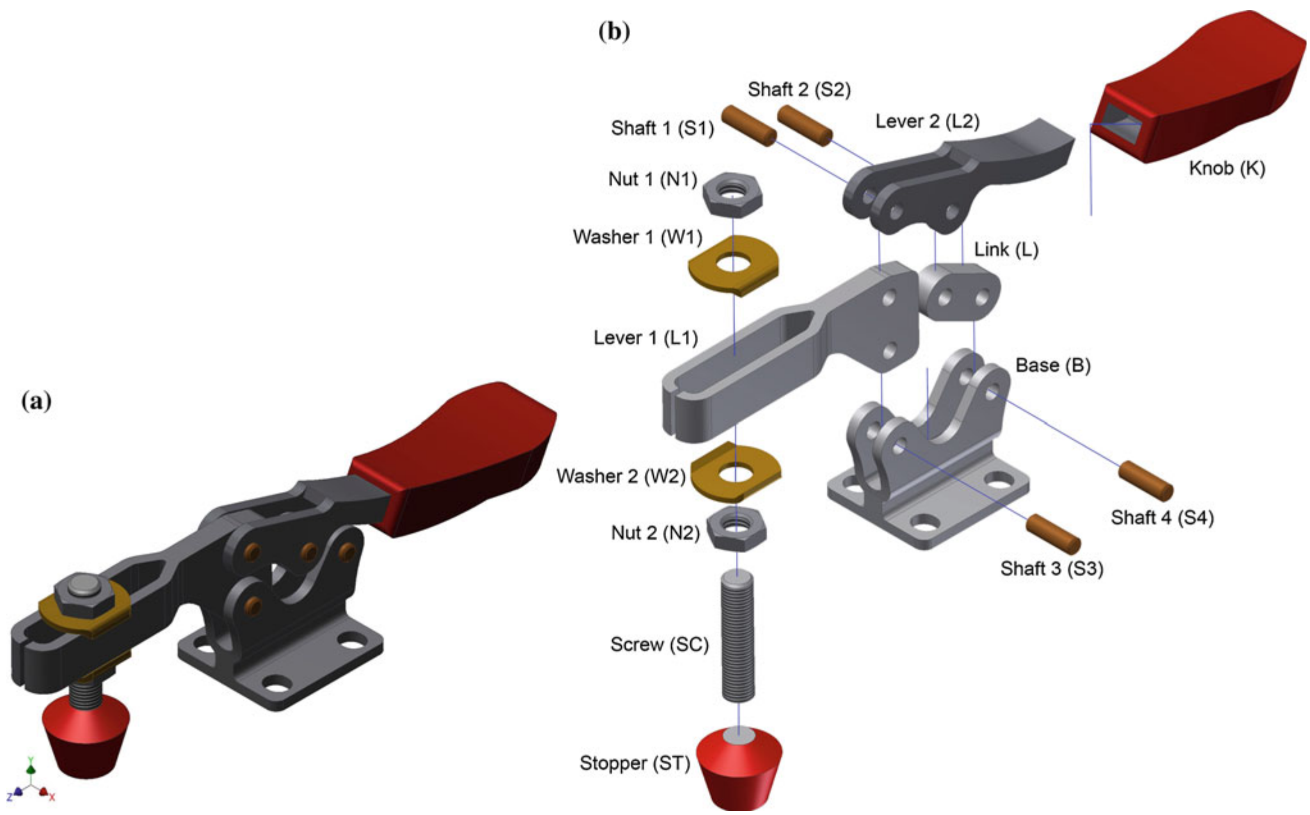

Fig. 4 CAD model and components of a standard horizontal handle hold-down clamp

(a)

	B	L1	L2	L	K	S1	S2	S3	S4	SC	ST	W1	W2	N1	N2
B		1	0	1	0	0	0	1	1	0	0	0	0	0	0
L1	1		1	0	0	1	0	1	0	0	0	1	1	0	0
L2	0	1		1	1	1	1	0	0	0	0	0	0	0	0
L	1	0	1		0	0	1	0	1	0	0	0	0	0	0
K	0	0	1	0		0	0	0	0	0	0	0	0	0	0
S1	0	1	1	0	0		0	0	0	0	0	0	0	0	0
S2	0	0	1	1	0	0		0	0	0	0	0	0	0	0
S3	1	1	0	0	0	0	0		0	0	0	0	0	0	0
S4	1	0	0	1	0	0	0	0		0	0	0	0	0	0
SC	0	0	0	0	0	0	0	0	0		1	0	0	1	1
ST	0	0	0	0	0	0	0	0	0	1		0	0	0	0
W1	0	1	0	0	0	0	0	0	0	0	0		0	1	0
W2	0	1	0	0	0	0	0	0	0	0	0	0		0	1
N1	0	0	0	0	0	0	0	0	0	1	0	1	0		0
N2	0	0	0	0	0	0	0	0	0	1	0	0	1	0	

(b)

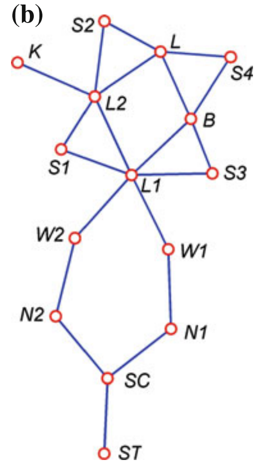

Fig. 5 **a** Adjacency matrix and **b** undirected graph

network to avoid enumeration of repeated cycles. Every node is then progressively explored until no further nodes remain in the network. In addition, the algorithm checks for all expanded nodes to find a node connected to the prior node, because this node should be on a straddling link of the cycle, if so, this node is removed from the path list of nodes for definition of the cycle.

The nodes of the undirected graph are evaluated and classified with a centrality index; $ICT_{(i)}$, related to the degree of the node, its relative participation about all the set of induced cycles of the graph, the mean degree of its neighbours and its weighted clustering coefficient. The centrality condition identifies which are the important nodes that must be assembled first than their corresponding neighbours, that is, the platform

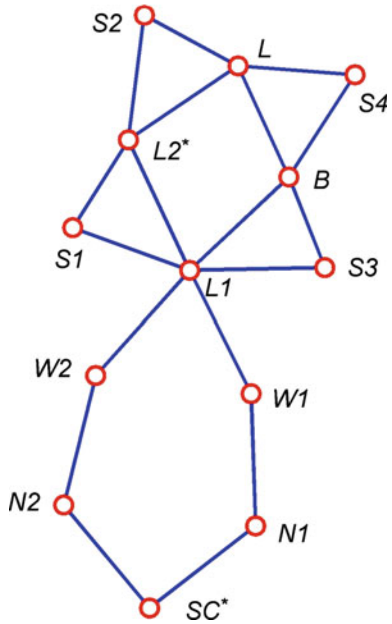

Fig. 6 Undirected graph after step 1. Reduction to nodes "SC*" and "L2*"

Table 1 Indexes for nodes and cycles in step 2

	Node	Centrality index, ICT
1	B	0,1562
2	***L1***	***0.2874***
3	L2*	0.1562
4	L	0.1618
5	S1	−0.0331
6	S2	−0.0219
7	S3	−0.0331
8	S4	−0.0219
9	SC*	0.0786
10	W1	0.0562
11	W2	0.0562
12	N1	0.0786
13	N2	0.0786
	Induced cycle	Importance index, ICI
1	***B-L1-L2*-L***	***0.2180***
2	B-L1-S3	0.1879
3	B-L-S4	0.1285
4	L1-L2*-S1	0.1879
5	L1-SC*-W1-W2-N1-N2	0.1493
6	L2*-L-S2	0.1285

component of the subassembly sequence. If more than one node is identified as a platform, all the possible sequences that depend from these nodes will be generated.

The induced cycles or the independent sub-assemblies are also evaluated and classified with an importance index; $ICI_{(i)}$, useful to identify both their level of interaction and the importance of their constituent nodes.

If two or more induced cycles present the same importance index they are reduced simultaneously in the same step of the approach. If they have different nodes there are possible assembly sequences as cycles are, but if they share nodes, the order of reduction of the cycles is according to the higher value of centrality index of the base nodes.

In this way, both the centrality index for each node and the importance index for each cycle are calculated, to identify the base node of the assembly sequence and the first cycle to be reduced, respectively.

With the undirected graph presented in Fig. 6, six induced cycles have been identified and, according to the importance index, *ICI*, the next subassembly is composed by the "base (B)", the "lever 1 (L1)", the subassembly "L2*" and the "link (L)" where the base node for the assembly sequence is the component "lever 1 (L1)" having the higher centrality index value, *ICT*. The values of such indexes are presented in the Table 1. For this subassembly, the sequences start from the base node and, respecting the liaisons reduction, $2^{(k-2)}$ sequences are generated, where k is the length of the concerned cycle, that is, four sequences because the cycle is formed by four nodes.

Having identified the subassembly to be mounted, the approach generates possible assembly sequences for that subgroup and reduces all components to the base node without generation of loops or doubled edges.

So, the induced cycle "B-L1-L-L2*" is reduced to its base node into the subassembly "L1*" as it is presented in the undirected graph of the Fig. 7.

4. STEP 3 At this point, the step to reduce nodes with degree value equal to one and the following step to identify induced cycles are iteratively applied until one cycle remains at the end. Then, each node of the cycle is considered as a possible base component and the sequences are generated for each component.

   In this case, the components "shaft 1 (S1)", "shaft 2 (S2)", "shaft 3 (S3)" and "shaft 4 (S4)" could be assembled to the new subassembly "L1*". So, the assembly graph is reduced to six nodes as it is shown in Fig. 8.
5. STEP 4 In this case, no more reductions are required and with the final cycle composed by six nodes, $6 \times 2 \times$

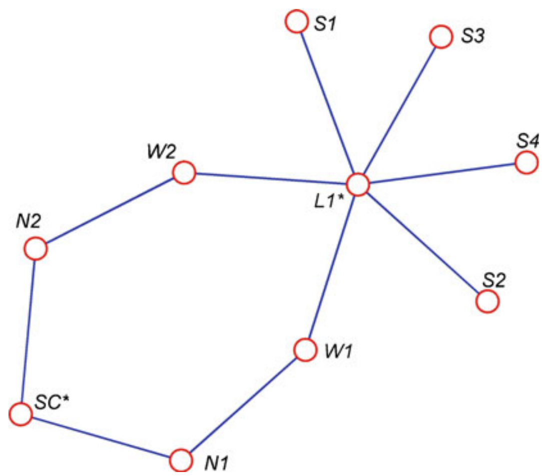

Fig. 7 Undirected graph after step 2. Reduction of cycles to node "L1*"

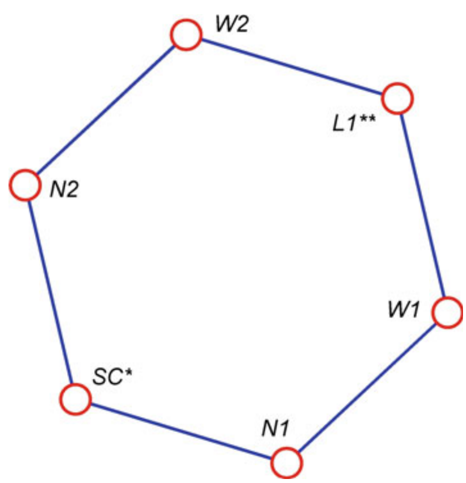

Fig. 8 Undirected graph after step 3

$(k-2) = 6 \times 2 \times (6-2) = 6 \times 16 = 96$, ninety six assembly sequences are obtained. That is, sixteen (16) assembly sequences starting from each node of the cycle.

So, the automated approach has arrived to the final assembly state, finding subassemblies at each step of the procedure.

The summary Table 2 presents all the sequences obtained for each subassembly identified in each step of the approach. This final result can be translated to any type of assembly representation presented in theory, such as either AND/OR graphs [6], directed graphs or graphical representation schemes.

The steps of the approach are considered like precedence in the assembly sequence and starting from the last sequences obtained at the last step, replacing the subassemblies of the previous steps, we finally have nine thousand two hundred sixteen ($96 \times 24 \times 4 \times 1 \times 1 = 9216$) possible assembly sequences for the whole product. Some obtained assembly sequences are shown in Table 3.

With this approach, it is possible to find at least one feasible assembly sequence if the product model is correctly constructed and conceived, since all the solutions are equivalent from a topological point of view. So, the user could evaluate and filter some potential solutions using technical parameters of the current assembly line, identifying preferred precedence relations or through implementation of virtual tools intended to visual evaluation, according to his/her experience. At this point would be interrogated in order to identify the feasible solutions.

Anyway, the number of queries can be reduced if the user evaluates the feasibility of the sequences for each subassembly obtained at each step of the procedure rather than their combination. In this way, the final number of possible assembly sequences corresponds to the multiplication among feasible assembly sequences for subassemblies obtained at each step of the process. This query-answer process must be executed observing the order of the steps, since an unfeasible subassembly is identified; the mechanical system should be reviewed.

The querying analysis for the clamp is presented in the Table 4 where ($1 + 1 + 4 + 24 + 96 = 126$) one hundred twenty six precedence questions should be answered. Here, in the three first steps of the procedures all the sequences are feasible and in the final step there are thirty two (32) feasible solutions from the ninety six (96) sequences automatically obtained.

In this way, after the querying, the first 9216 assembly sequences are reduced to ($1 \times 1 \times 4 \times 24 \times 32 = 3{,}072$) three thousand seventy two feasible assembly sequences, as it is presented in the Table 5.

Here, taking advantage of this representative example, it is worth noticing that this automatic approach is independent of the analysis of the virtual model and no considerations about either the modelling technique or the nature of the parts are required for the implementation of the approach. In this way, all the components of the product are considered in the analysis even if the number of assembly sequences is considerably sensitive to this. In the clamp example, each shaft is considered individually and, hence, twenty four sequences for their sub-assembly are generated.

Otherwise, the user could be interested in a previous analysis of the model in order to identify some patterns of specific elements to be neglected in the assembly sequence analysis with the purpose of reducing the number of solutions. This approach has been identified in some researches in order to improve the analysis and to reduce the human participation.

In the clamp example, the shafts "S1", "S2", "S3" and "S4" could be neglected in the analysis since they are directly

Table 2 Subassembly sequences for each step of the approach

Step	Subassembly components	Base node	Possible assembly sequences		Subassembly name
			Qty	Precedence	
1	K-L2	L2	1	L2 < K	L2*
	ST-SC	SC	1	SC < ST	SC*
				L1 < L2* < L < B	
2	B-L1-L2-L	L1	4	L1 < B < L < L2*	L1*
				L1 < L2* < B < L	
				L1 < B < L2* < L	
				L1* < S1 < S2 < S3 < S4	
				L1* < S1 < S2 < S4 < S3	
	S1-L1*			L1* < S1 < S3 < S2 < S4	
	S2-L1*			L1* < S1 < S3 < S4 < S2	
3	S3-L1*	L1*	24	….	L1**
	S4-L1*			L1* < S4 < S2 < S1 < S3	
				L1* < S4 < S2 < S3 < S1	
				L1* < S4 < S3 < S1 < S2	
				L1* < S4 < S3 < S2 < S1	
				L1** < W2 < N2 < SC* < N1 < W1	
				L1** < W2 < N2 < SC* < W1 < N1	
		L1**		L1** < W2 < N2 < W1 < N1 < SC*	
		SC*		L1** < W2 < N2 < W1 < SC* < N1	Final assembly
4	L1**-SC*-W1-N1-W2-N2	W1	96	….	
		N1		N2 < W2 < L1** < SC* < N1 < W1	
		W2		N2 < W2 < L1** < SC* < W1 < N1	
		N2		N2 < W2 < L1** < W1 < SC* < N1	
				N2 < W2 < L1** < W1 < N1 < SC*	

Table 3 Obtained assembly sequences for the whole product

No.	Assembly sequence
1	L1 < L2 < K < L < B < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < N1 < W1
2	L1 < B < L < L2 < K < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < N1 < W1
3	L1 < L2 < K < B < L < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < N1 < W1
4	L1 < B < L2 < K < L < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < N1 < W1
⋮	⋮
9,213	N2 < W2 < L1 < L2 < K < L < B < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
9,214	N2 < W2 < L1 < B < L < L2 < K < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
9,215	N2 < W2 < L1 < L2 < K < B < L < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
9,216	N2 < W2 < L1 < B < L2 < K < L < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST

related to the joining process of the components “L1”, “L2”, “L” and “B” or they could be summarized into a unique component “shaft”. In the first case, not considering the shafts, the automated solutions could be reduced to $(1 \times 1 \times 4 \times 96 = 384)$ three hundred eighty four solutions and with the feasibility analysis, there are $(1 \times 1 \times 4 \times 32 = 128)$ one hundred twenty eight feasible solutions.

De Fazio and Whitney [8], in their example for the assembly sequence analysis of a transmission for trucks, do not consider fasteners in the analysis since they assume that when two parts secured by threaded fasteners are mated, they are placed and secured. In this way, these components are transparent to the approach when not represented by nodes. The authors have analysed this specific bibliographic

Table 4 Feasibility analysis for each sequence of the identified sub-assemblies

Step	Subassembly components	Base node	Possible assembly sequences		Subassembly name	Feasibility
			Qty	Precedence		
1	K-L2	L2	1	L2 < K	L2*	Yes
	ST-SC	SC	1	SC < ST	SC*	Yes
				L1 < L2* < L < B		Yes
2	B-L1-L2-L	L1	4	L1 < B < L < L2*	L1*	Yes
				L1 < L2* < B < L		Yes
				L1 < B < L2* < L		Yes
				L1* < S1 < S2 < S3 < S4		Yes
				L1* < S1 < S2 < S4 < S3		Yes
	S1-L1*			L1* < S1 < S3 < S2 < S4		Yes
	S2-L1*			L1* < S1 < S3 < S4 < S2		Yes
3	S3-L1*	L1*	24	….	L1**	Yes
	S4-L1*			L1* < S4 < S2 < S1 < S3		Yes
				L1* < S4 < S2 < S3 < S1		Yes
				L1* < S4 < S3 < S1 < S2		Yes
				L1* < S4 < S3 < S2 < S1		Yes
				L1** < W2 < N2 < SC* < N1 < W1		No
		L1**		L1** < W2 < N2 < SC* < W1 < N1		Yes
		SC*		L1** < W2 < N2 < W1 < N1 < SC*		Yes
		W1		L1** < W2 < N2 < W1 < SC* < N1	Final assembly	Yes
4	L1**-SC*-W1-N1-W2-N2	N1	96	….		No
		W2		N2 < W2 < L1** < SC* < N1 < W1		No
		N2		N2 < W2 < L1** < SC* < W1 < N1		Yes
				N2 < W2 < L1** < W1 < SC* < N1		Yes
				N2 < W2 < L1** < W1 < N1 < SC*		Yes

Table 5 Feasible assembly sequences obtained after the feasibility querying

No.	Assembly sequence
1	L1 < L2 < K < L < B < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < W1 < N1
2	L1 < B < L < L2 < K < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < W1 < N1
3	L1 < L2 < K < B < L < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < W1 < N1
4	L1 < B < L2 < K < L < S1 < S2 < S3 < S4 < W2 < N2 < SC < ST < W1 < N1
⋮	⋮
3,069	N2 < W2 < L1 < L2 < K < L < B < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
3,070	N2 < W2 < L1 < B < L < L2 < K < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
3,071	N2 < W2 < L1 < L2 < K < B < L < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST
3,072	N2 < W2 < L1 < B < L2 < K < L < S4 < S3 < S2 < S1 < W1 < N1 < SC < ST

example achieving 96 different feasible and unfeasible assembly sequences in contrast with the 440 possible assembly sequences obtained with the De Fazio and Whitney's method [23].

So, this proposed automatic approach allows automatically obtaining a lower number of possible assembly sequences respecting to theoretical approaches based on querying and answering techniques. Besides, the information required for its implementation could be retrieved in early stages of design with rough conceptual virtual models.

7 Conclusions

The proposed method is able to obtain automatically at least one feasible assembly sequence of the product, starting from the topological information and the interaction among its parts, enclosed in the CAD model. This approach allows specialized or non-specialized personnel to obtain initial feasible assembly sequences already during the early phases of the product design and development process.

Owing to the nature of information required (contact or interference) no dimensional or material information is required to be included into the assembly model, making this approach very suitable for assembly sequence generation starting from 3D layouts of solution principles identified at the conceptual and embodiment stages of design. It is worth noticing the impact of the CAD model configuration and the functional nature of the parts concerning the number of assembly sequences obtained with this approach, in this way, could be interesting to check the "wellness" of the CAD model before its use in order to avoid a great number of solutions.

Otherwise, if not a single feasible solution is obtained; this situation indicates that such mechanical system design should be controlled in order to identify instability or over constrained conditions.

The sub-assembly identification approach is adequate to industrial configurations where multiple assembly workstations are introduced in order to speed the product process up, since the assembly plan offers parallelism and flexibility in assembly when independent subassemblies are identified. According to this, it would be interesting to observe the table with the assembly sequences for identified sub-assemblies pointing to the definition and positioning of workstations in the assembly line.

It is expected that such proposed methodology opens a possibility for better integration of assembly planning topics into the early stages of design in order to reduce product development time and cost and to increase the product quality.

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