# ASPIP – AUTOMATIC AND ASSISTED DEFINITION OF ASSEMBLY SEQUENCES BASED ON COMPONENT LIAISONS AND SUBASSEMBLIES APPROACH

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**ABSTRACT:** The design process of industrial products considers different aspects of the product lifecycle to make decisions about the functionality, manufacturability, usability, among other aspects related to the user interaction. Assembly sequence definition is an important phase of the product development process that is normally defined during the detailed design stage, and it is mainly based on skill and experience of manufacturing designers. The prospect to automatically identify possible assembly sequences at early stages of the design process, starting from contact or liaison information between components extracted from 3D CAD models would lead up to reduce time and costs, and would give interactive information for support designers during decision making activities. In this way, authors propose a computer application, so called Automatic Sequence Planner for Industrial Products (ASPIP), to automatically identify assembly sequences of an industrial product. The core of the application is based on an existent approach for Assembly Sequence Analysis, which is followed and presented step by step to enable the designer to create the assembly sequence. The tool enables the analysis of the liaison graph of the components of the product, which is automatically obtained from a kinematically stable CAD model, and automatically obtains a list of assembly sequences with at least one feasible sequence. The assembly sequence analysis of an industrial product is presented as a validation of the functionality of the application ASPIP.

**KEYWORDS**: *Assembly Sequence Planning; Assembly Sequence Analysis; Feasible Assembly Sequence; Assembly Modeling Liaisons; Computer Aided Systems*

## 1.0 INTRODUCTION

Tools intended to support designers during their work are focused on the reduction of both the time and costs of the product design process. This trend applies to the evaluation of information available as far as possible at early stages of product design to allow the designer to radically compare different solutions rather than proceeding with fine tuning of a single option that may be revealed not feasible at the end of the process. This is true for many choices taken during the process of selection of the product solution and of its embodiment, but it is equally true when the evaluation of aspects related to other following tasks of the design process is required. Specifically, assembly planning is one of the most critical phases of the product design process since more than 40% of the manufacturing cost of a product is spent on assembly [1]. Then, the study of the assembly process of the product at early stages of the design process would allow to obtain useful information for decision making. However, despite the introduction of sophisticated tools in the design process, the analysis and planning of an assembly are still mainly intuitive, heuristic, and lengthy processes developed in manual manner, at final stages of development, by a skilled manufacturer with knowledge-based methods. Even with the help of soft computing techniques, such as Artificial Intelligence (AI), the predicate analysis and the analysis of assembly constraints are structured by manufacturing staff [2]. The character of the task often does not allow the exploration of all the feasible alternatives, reducing the search of the possible assembly sequences to few solutions. Generally, only one sequence is selected and adopted on the base of the skills and knowledge of the manufacturer without evaluating if more efficient sequences could exist. Therefore, to improve the assembly plan definition of the product, an analysis of all feasible assembly sequences could be useful. This analysis can help the manufacturer to choose an efficient assembly sequence oriented to the optimization of the process regarding different targets, such as the reduction of the overall assembly process costs, by reducing the number of the fixture and tool changes or the number of reorientations during assembly tasks, among other aspects [3]. Unfortunately, this analysis could often result impracticable at industrial level because of the long time required to generate all the assembly sequences of the product.

It is also necessary to consider that one of the main questions regarding the analysis of the assembly is related to the real number of feasible assembly sequences for the product and for all its sub-assemblies. Obtaining this information in automatic manner may allow to reduce the time spent in the assembly process definition, and to consider a greater number of feasible sequences without adopt the first one solution selected on the base of designer skills. Besides, it could be useful to support the learning process of young engineers.

Another useful information derived from the analysis of the assembly allows to arrange the model structure in different manner; for example, grouping components into sub-assemblies, reducing the complexity of the model, and encouraging a better management of the overall assembly. So, an automated tool to manage information regarding product parts from an assembly point of view, to analyze the interactions between neighboring geometric regions, and oriented to generate feasible assembly solutions could better satisfy the company needs set against methodologies based on the human experience. In this way, a software application, so called Automatic Sequence Planner for Industrial Products (ASPIP), has been developed to identify possible assembly sequences and to guide the assembly planning process starting from an adjacency matrix of the components of the product, derived from a CAD modelling software and processed with some modified algorithms of the graph theory.

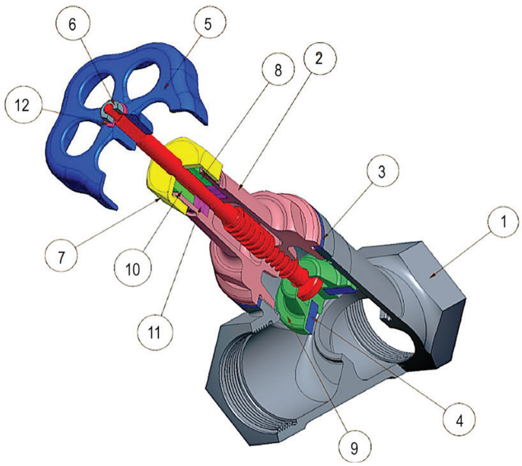
## 1.1 Liaisons Graphs Representation for Assembly Analysis and Software Approaches

In the past years, many research projects have been conducted in the assembly analysis field and its automation. The studies as shown in [2, 4-7], have widely researched about Assembly Sequence Planning (ASP), considered as a NP hard problem, analyzing different approaches, from graph theory to artificial intelligence, to obtain qualitative and quantitative information of the assembly of products, from 3D CAD models and experts experience, in order to eliminate the non-possible assembly sequences applying four predicates: liaisons, geometrical feasibility, mechanical feasibility, and stability. The purpose of these studies was to identify both the feasible assembly sequences and the best assembly tasks. This goal was pursued identifying the feasible sequences on the base of technical decision rules or precedence relationships among the parts suggested by querying of skilled staff about the assembly process [8-10]. Methods focused on the use of CAD assembly model and assembly tiers [11-15], are based on the knowledge of an assembly state for the product, but they still need human intervention. The basic approach to problem solving in Assembly Sequence Analysis (ASA) is the systematic search of feasible assembly sequences into the problem domain defined for a product architecture. The search of the assembly sequence for a product can be addressed, without any other information, through a combinatorial approach that considers all the parts of the assembly. This approach leads to an explosion in the number of possible solutions for the problem. In fact, the number of the combinations representing all the sequences adoptable for assembling a product composed by n parts, without knowing the assembly liaisons among them, is n!

Clearly, facing the problem in such a brutal manner and without some systematic criteria leads to several solutions impossible to verify and to an activity very expensive for the industry. The way to reduce the number of the combinatorial sequences is to introduce some conditions in the calculus related to different predicates or, even, with enriched semantic foundation [6, 16]. The simpler condition that could be introduced derives on the analysis of the connections existing between the parts that is by their mating in the assembly. On the base of this condition, it is possible to graphically describe the assembly of a product by means of a liaisons graph, where the nodes represent the parts of the product while the edges show the mating connections between the parts, and the cost of the assembly relations could be computed with a weighted graph with qualitative and quantitative constraints [17-19].

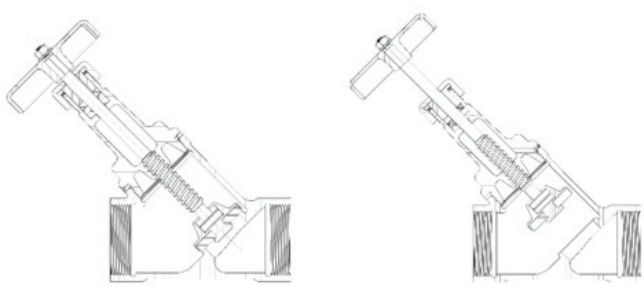
Many authors have proposed to extract the liaisons graph of an assembly directly from the drawing with the support of skills technicians [20-23], while others have adopted different techniques to extract them directly by a computer aided model of the assembly [24-25], but always managed with human support, even those solutions based on soft computing to optimize different objectives in the ASP [2, 26-27]. Current CAD systems allow to obtain useful data to generate the liaisons graph and other assembly properties by means of simple queries. An efficient method to create the assembly liaisons graph of a product is to consider the spatial interaction among the parts through the interference between their mated surfaces [28]. This approach bases its assumption on a formally correct CAD model, that is a model where all parts are fixed in a stable position, from a kinematic point of view, and that two parts are mated between them if at least two surfaces of them are in contact (zero interference) or in interference. The hypothesis that a stable assembly is necessary to define the liaisons graph of an industrial product is based on the consideration that, in industrial field, a part that is not in contact with at least another part of the same assembly does not exist. For this statement, the 3D CAD model adopted to generate the liaisons graph should be well defined, as well as, today, the totality of the CAD assembly models used to generate real industrial products are defined with assembly connections.

Considering the generation of the liaisons graph for an assembly based on the search of the interactions between the parts, there are some interesting cases that should be considered in the analysis of the obtained graph, and that are influenced by the standard representation adopted in the industry. For example, the valve shown in Figure 1 presents some notable elements supporting this statement. Figure 2 shows the product in two operational conditions such as closed valve and open valve while the liaisons graphs obtained in both cases are presented in Figure 3.



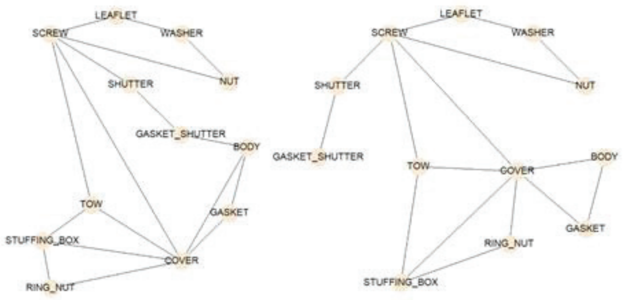

| Pos. | Q.ty | Name |
|---|---|---|
| 1 | 1 | BODY |
| 2 | 1 | COVER |
| 3 | 1 | GASKET |
| 4 | 1 | GASKET_SHUTTER |
| 5 | 1 | LEAFLET |
| 6 | 1 | NUT |
| 7 | 1 | RING_NUT |
| 8 | 1 | SCREW |
| 9 | 1 | SHUTTER |
| 10 | 1 | STUFFING_BOX |
| 11 | 1 | TOW |
| 12 | 1 | WASHER |

Figure 1: Valve with bill of materials



(a) (b)

Figure 2: Operational states of the valve namely (a) closed valve and (b) open valve




(a) (b)

Figure 3: Valve operational liaisons graphs namely (a) closed valve and (b) open valve

Both graphs differ, since the liaison between the "gasket_shutter" and the "body" disappears when the valve is open, and lead to a different number of assembly sequences. In fact, with the closed valve the number of generated sequences is more than ten million, while with the open valve there are about three hundred eighty thousand possible combinations derived from the graph, before the reduction step of feasibility evaluation. An approach modified from Viganò and Gómez [29] and subsequently implemented into the ASPIP software is presented next section.

## 1.2 Approach for Assembly Sequence Definition

The proposed approach implemented in the ASPIP application is intended to identify and categorize possible sub-assemblies inside the liaisons graph of the assembly through the evaluation of indices of importance for both components and induced cycles, which would allow to evaluate the connectivity level of both components and subassemblies in order to identify more realistic feasible assembly sequences, but considering all the possible combinations between the sequences generated for all the possible subassemblies, or induced cycles. In this way, ASPIP allows to choose or not the consideration of the importance indices during the analysis and generation process, to reduce or extend the solution domain, respectively.

The procedure bases its choices only on the existence of interactions between the components. Other criteria such as manufacturability and product strategy are not considered for the generation of sequences. The complexity of the problem for the extraction of the feasible assembly sequences is reduced through the identification of independent sub-assemblies. The effectiveness of this route has been also demonstrated in the study on large real-world issues and as an approach for the minimization of the disassembly task cost [18, 30-31].

The automated proposed approach, modified by adding steps (iv) and (ix), considers the following general steps:

i. Analysis of the CAD assembly to retrieve contact information required to generate the adjacency matrix and the liaisons graph of the model.
ii. Detecting parts with degree value equal to "one" if they exist. This special situation considers one part mated only with another and, under that one condition, these two parts can be immediately assembled obtaining a sub-group.
iii. Identification of induced cycles available into the liaisons graph through a modified Breadth-Depth First Search algorithm.
iv. Detecting isolated cycles that have only one node connected with the other cycles of the graph. These cycles are managed as sub-assemblies that can be assembled at the beginning or at the end of the product assembly.
v. Ranking of nodes based on the centrality index, $I_N$, which defines the relation of importance of a part with respect to the other parts in the assembly [29].
vi. Ranking of cycles based on their importance index, $I_C$, that is the inner and outer positions of each cycle into the undirected liaisons graph [29].
vii. Sub-assembly identification. At this point the cycle with a higher value of importance index, $I_C$, is selected as the initial sub-assembly and its node with greater value of centrality index, $I_N$, is identified as the base node of the sequence.
viii. Sub-assembly reduction. The assembly sequences for the identified sub-assembly have been generated and all the components of the cycle have been reduced to the base node.
ix. Connectivity evaluation for each generated assembly sequence considering connectivity or existence of an edge between consecutive parts reported in the sequence, in order to reduce the number of solutions and to guarantee the feasibility of the solution from a connectivity point of view.
x. Return to the second step and repeat previous steps until the last remaining induced cycle is analyzed and reduced. At this point, each node of the cycle is considered as a possible base component and sequences are generated for each one.

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 of the number of sequences found for each step. These solutions are equivalent from a topological point of view and a manufacturer can filter it using technical parameters of the current assembly line, identifying preferred precedence relations or through implementation of virtual tools intended to visual evaluation.

## 2.0 ASPIP IMPLEMENTATION

The proposed approach was implemented into a software application, so called Automatic Sequence Planner for Industrial Products (ASPIP), to verify its ability to solve different assembly problems and to generate feasible assembly sequences for a product in automatic manner. It was developed to follow and show any single step of the procedure, to obtain some other useful information that might be otherwise hidden, and to bias the extraction of assembly sequences based on the criteria governed by the user.

In the case of the undirected liaisons graph for the open valve shown in the Figure 3 (b), the software initially reduces, in two steps, the nodes "Gasket_Shutter" and "Shutter", as it is presented in Figure 4.

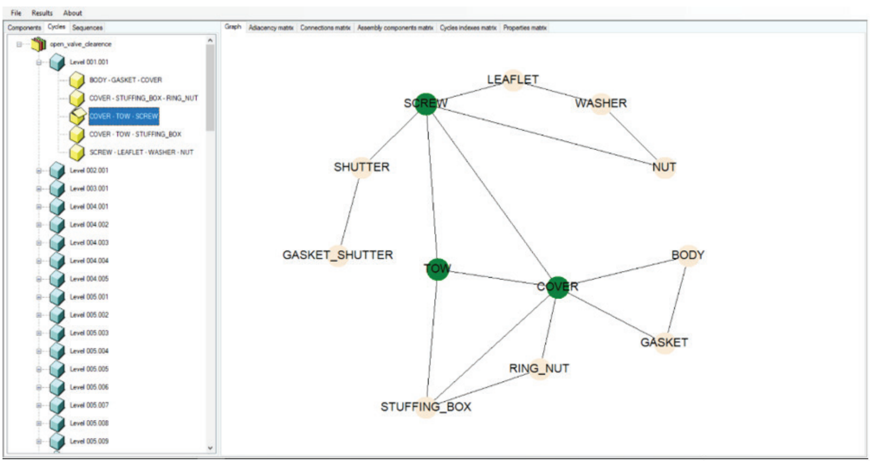



Figure 4: First reduction step of the nodes with degree "one" for valve assembly

After the reduction, the software identifies all the induced cycles, as it is shown in Figure 5, then, excludes two isolated induced cycles like "Gasket-Body-Cover" and "Nut-Washer-Leaflet-Screw" concentrating the research of the sequences able to assembly the main product sub-assembly, composed by "Cover-Tow-Stuffing_Box-Ring_Nut-Screw" parts.

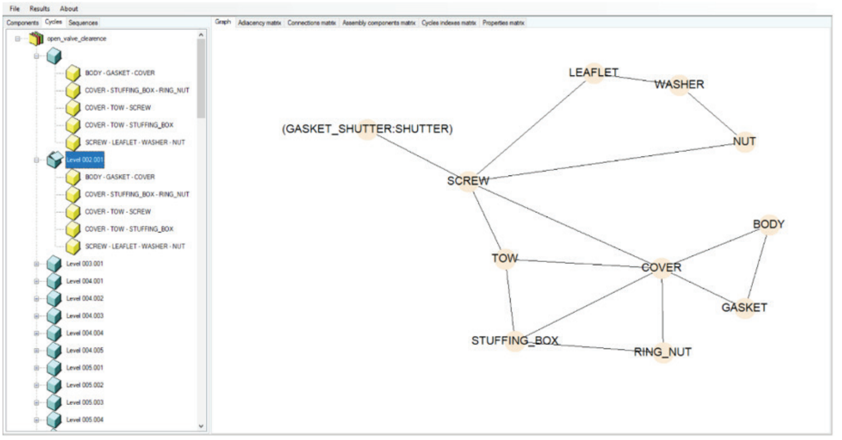
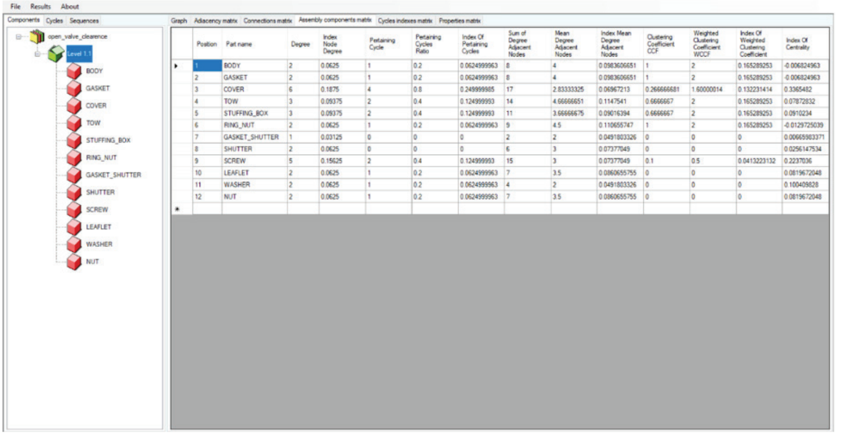



Figure 5: List of the induced cycles identified at any single reduction step

Next, the software calculates the centrality index, $I_N$, for each node, as it is presented in Figure 6 and the importance of the induced cycles is calculated with the index, $I_C$.



| Position | Part name | Degree | Index Node Degree | Pertaining Cycle | Pertaining Cycles Ratio | Index Of Pertaining Cycles | Sum of Degree Adjacent Nodes | Mean Degree Adjacent Nodes | Index Mean Degree Adjacent Nodes | Clustering Coefficient CCF | Weighted Clustering Coefficient WCCF | Index Of Weighted Clustering Coefficient | Index Of Centrality |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | BODY | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 8 | 4 | 0.0983606651 | 1 | 2 | 0.165289253 | -0.006824963 |
| 2 | GASKET | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 8 | 4 | 0.0983606651 | 1 | 2 | 0.165289253 | -0.006824963 |
| 3 | COVER | 6 | 0.1875 | 4 | 0.8 | 0.249999985 | 17 | 2.83333325 | 0.06967213 | 0.266666681 | 1.60000014 | 0.132231414 | 0.3365482 |
| 4 | TOW | 3 | 0.09375 | 2 | 0.4 | 0.124999993 | 14 | 4.66666651 | 0.1147541 | 0.6666667 | 2 | 0.165289253 | 0.07872832 |
| 5 | STUFFING_BOX | 3 | 0.09375 | 2 | 0.4 | 0.124999993 | 11 | 3.66666675 | 0.09016394 | 0.6666667 | 2 | 0.165289253 | 0.0910234 |
| 6 | RING_NUT | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 9 | 4.5 | 0.110655747 | 1 | 2 | 0.165289253 | -0.0129725039 |
| 7 | GASKET_SHUTTER | 1 | 0.03125 | 0 | 0 | 0 | 2 | 2 | 0.0491803326 | 0 | 0 | 0 | 0.00665983371 |
| 8 | SHUTTER | 2 | 0.0625 | 0 | 0 | 0 | 6 | 3 | 0.07377049 | 0 | 0 | 0 | 0.0256147534 |
| 9 | SCREW | 5 | 0.15625 | 2 | 0.4 | 0.124999993 | 15 | 3 | 0.07377049 | 0.1 | 0.5 | 0.0413223132 | 0.2237036 |
| 10 | LEAFLET | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 7 | 3.5 | 0.0860655755 | 0 | 0 | 0 | 0.0819672048 |
| 11 | WASHER | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 4 | 2 | 0.0491803326 | 0 | 0 | 0 | 0.100409828 |
| 12 | NUT | 2 | 0.0625 | 1 | 0.2 | 0.0624999963 | 7 | 3.5 | 0.0860655755 | 0 | 0 | 0 | 0.0819672048 |

Figure 6: List of the calculated values of the centrality indices for all nodes

The result of this analysis is the list of 11 sequences presented in Table 1. These sequences were extracted from 240 sequences generated considering only the graph of the main sub-assembly of the valve.

Table 1: Sequences obtained for the main sub-assembly of valve

| | | PARTS | | | | |
|---|---|---|---|---|---|---|
| SEQUENCES | A | COVER | TOW | STUFFING_BOX | RING_NUT | SCREW |
| | B | SCREW | COVER | TOW | STUFFING_BOX | RING_NUT |
| | C | RING_NUT | COVER | STUFFING_BOX | TOW | SCREW |
| | D | COVER | STUFFING_BOX | TOW | RING_NUT | SCREW |
| | E | TOW | COVER | STUFFING_BOX | RING_NUT | SCREW |
| | F | SCREW | TOW | COVER | STUFFING_BOX | RING_NUT |
| | G | TOW | STUFFING_BOX | COVER | RING_NUT | SCREW |
| | H | COVER | TOW | STUFFING_BOX | SCREW | RING_NUT |
| | I | COVER | STUFFING_BOX | TOW | SCREW | RING_NUT |
| | J | STUFFING_BOX | COVER | TOW | SCREW | RING_NUT |
| | K | STUFFING_BOX | TOW | COVER | SCREW | RING_NUT |

With a limited number of the sequences to consider, it is easy to evaluate which of them are feasible and which are not. It is possible to observe that only the sequence B is achievable, while sequences A, E, G, H and K are good only if you consider locking the “Ring_Nut” when the “Screw” is already mounted. The other sequences in Table 1 are not achievable. For these sequences, it is necessary to add the combination of the four sequences derived by the reduction of the two induced cycles (“Gasket-Body-Cover” and “Nut-Washer-Leaflet-Screw”) and the sequences derived by the reduction of "Gasket_Shutter" and "Shutter" nodes.

## 3.0 RESULTS AND DISCUSSION

The capability of the software to report the information at the end of each step, following the progress of the analysis, allows the designer to identify feasible and unfeasible sequences in order to guide the subsequent steps, or if a greater solution domain is to be explored, the whole analysis could be carried out in automatic manner. The user could also perform a feasibility analysis through a query-based procedure for each of the intermediate or final solutions [32]. The only constraint is that this query-answer process must be executed observing the order of the steps. Besides, the identification of independent sub-assemblies could be useful to consider the introduction of workstations oriented to a more flexible and parallel manufacturing process.

The software was tested with different types of assemblies, obtaining encouraging results and allowing to discover some particularities included into the 3D models of industrial assemblies. Some of these particularities have been already included into the last releases of the application, while others are already under study to evaluate their capacity to improve the generation of the feasible sequences for the assembly. One of these possible improvement regards the use of other available and extractable information from the 3D model of the product. This information is directly connected with specific properties of the single part, for example, the mass, volume, or surface values, expecting that the use of these properties might allow to obtain indices able to sort the list of the sequences according to its feasibility.

The proposed approach is based only on the topological information about the contact among the assembly parts, and it does not require the intervention of the user to define the liaison graph. For this it could also be adopted to check the "wellness" of the model further than to suggest a better arrangement of its parts organization.

## 4.0 CONCLUSION

Obtaining product assembly sequences, and related information, is of great interest for both skilled and not-skilled technicians, especially if such information can be obtained and analyzed from the first stages of the product design process. This is possible, when at early design stages as conceptualization, the proposed solutions could be sketched with rough 3D models, considering contacts between parts. Then, having the proposed Assembly Sequence Analysis (ASA) approach and the software ASPIP to automatically obtain at least one feasible assembly sequence of the product could aid the decision-making process in many cases. It is expected that it would open a possibility for better integration of assembly planning topics into the early stages of design to reduce product development time and cost and to increase the product quality. The proposed ASA approach presents a well-defined sequence of steps which allows to analyze the product from a point of view of contacts between components, defining indices for importance of parts and possible independent subassemblies according to their level of connectivity and interaction, in order to arrive at the end to a list of assembly sequences, where their feasibility could be analyzed according to different targets of optimization such as space, time or cost. Besides, the software allows the user to take decisions about the path of solution for each step, based on the experience or particular situations.

The presented case study made evident the different steps of the reduction of the liaisons graph in independent subassemblies, where the designer could analyze or not the feasibility of the resultant sub sequences and variate the solution domain, and a list of limited assembly sequences is obtained, with at least one feasible assembly sequence. The list allows the designer to explore different assembly approaches and design considerations for the different subassemblies or the whole product. The approach could be useful in many other engineering analyses where the connections among the parts are one of the information required for the study. For example, it would be possible to consider the use of the proposed approach in studies to predict change propagation in the products or, to define new assembly sequences considering also the time variable, as it happens in the definition of the assembly of industrial plants.

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