Computer Aided Mechanical Assembly Sequence Planning

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Abstract

The article presents and characterises the method of assembly sequence planning in the process of components and machine units design. The concept is based on the assumption that the method should help the engineer-constructor in specifying the best assembly sequence, taking into account the rules of design for assembly at an early stage of a product design development. Later on, the author discusses a practical application of the method on the basis of its computer implementation.

Keywords: assembly sequence planning, cad, design for assembly, engineering design

1 Introduction

Traditional process of a product manufacturing, which is characterised by a sequential design development and making of the product, does not allow to complete the operation in a short time and at a low cost, retaining its high quality. Design of products adapted to easy and cheap assembly is essential on account of the possibility of cost reduction of the production technological preparation and possible structural changes [1,3,4,12]. Taking into consideration the assembly process requirements (as well as other processes in the product development) should take place at a possibly early stage of the design [4,8,11,12]. It is then feasible to apply the methodology of concurrent design, which is based on taking into account, at every stage of the project, requirements for an entire life cycle of the product. This means the earliest possible identification of the structure features influence on all the important product characteristics [4,11].

The importance of the assembly process for the manufacturing costs suggests this process should be introduced during the product structure development. In the assembly process it is crucial to implement the sequence of its particular operations in a proper and efficient way.

In the literature one can find a lot of views on the assembly sequence generating. Bourjault [5] formulated an algorithm for generating all the permissible assembly sequences, which was based on a list of questions. These questions resulted in obtaining relations for the analysed constituents of a product. A similar algorithm is the one by De Fazio and Whitney [6], however it is based on determining relations for assembly operations, which characterise pairs of combined parts. Sanderson and Homem de Mello [10] developed an algorithm allowing to build a relational model, on the basis of which, using graph operations (graph cuts of and/or type), a set of all the possible assembly sequences was gained. Other studies related to determining the assembly sequences use for instance exploded views of the products, artificial intelligence methods. All the above approaches are applicable in the case of a previously developed product structure. Similarly, other approaches make the analysis of the assembly process possible, but only after the manufacturing stage, when the product components are ready and their assembly process is planned [2,7,9]. In this case any construction changes are really expensive and involve redesign of the product and repeated production of components which have undergone construction changes.

Most of the methods found in the literature can be applied only after the design process is completed, when the structural form of the product is known in details. It would be far better if the designer included the assembly requirements at the early stage of the product's design. Basing on this data he or she would be able to designate the best assembly sequence. It is possible then to make use of the concurrent design and planning of the assembly process, which considerably shortens the time required to introduce the product into the market.

2 Easyassemble method

The proposed method for planning the best assembly sequence called Easyassemble includes the requirements of 'design for assembly' methodology, which provides opportunity to use it at the early stages of machine and mechanical device design [3,11].

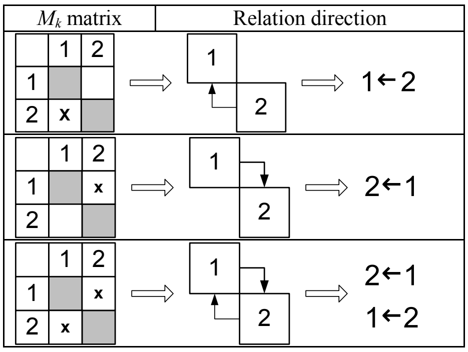
Simple principles of combining two parts, which are described in literature [11] are used in the proposed method. Thus, a possibility of evaluating the structure at the devising stage, where the details of the structure are not yet determined, was achieved. This method is also useful in relation to assessment of already designed structures and such an example is presented in the article.

In this method four basic, completed one by one modules can be distinguished: a record of the product design structure, evaluation of defined assembly connections, defining of constraints, and an algorithm for generating permissible assembly sequences.

2.1 Representation of the design structure

All contact relations between the components of the product are identified on the basis of the design documentation. Contact relation is understood as the possibility of combining two parts. Established relations (connections) are stored in the form of a graph and the corresponding matrix - called further the relationship matrix or structure design matrix - M_k. This matrix has a size of n x n, where n is the number of the product components. Relations between the product components can assume three forms. They are presented in the **Table 1**.

Table 1 Forms of the matrix record of components' connections



If there is no relation between the parts (or if it is not possible to connect two parts), no type of relation is assigned and the corresponding M_k matrix field stays empty.

2.2 Estimation of attributes of the assembling operations

To evaluate a combination of two parts the q_a [3] indicator was taken from literature and applied. It was developed on the basis of experts' knowledge and multiple analyses conducted in actual companies. The indicator was used to assess the set of connections defined earlier in the form of M_k matrix in order to evaluate assembly sequences and find the best ones in the generated set. Moreover, it is assumed that it is going to be used to obtain information on the degree of complexity of the analysed structure and its component parts.

The possibility of defining values other than in the original study has been introduced. The values serve to evaluate particular components of the q_a indicator. This gives a chance to adjust the assessment with the use of q_a indicator to the specific conditions of a particular company, in which literature indicators would be wrongly applied for various reasons. In addition, the assessment value could be represented by cost or connection realisation time, which would facilitate defining of sequences characterised by the shortest time or the lowest realisation cost.

The components of the indicator $q_a = h_p \cdot f_p$ [3] are:
– indicator h_p for feeding and grabbing the element,
– indicator f_p for elements connection.

The indicator $f_p = A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \cdot H$ includes:
– A - correctness of parts connection in relation to a unit function,
– B - requirement of precise mutual positioning of two joined parts,
– C - joined parts orientation,
– D - direction of parts connection,
– E - type of parts connection, depending on the contact surface between them,
– F - limited access and/or connection control
– G - alignment and other possible obstacles,
– H - resistance in parts connecting.

The indicator h_p depends on feeding and the element sensitivity. It includes three feeding options:
– manual feeding and grabbing,
– feeding with the use of a feed mechanism (feeding: mechanical, subatmospheric, magnetic),
– automatic feeding (considering: a feed mechanism, transporter; grabbing: automatic, subatmospheric, magnetic).

A component sensitivity depends on its susceptibility to mechanical damage, temperature changes, and pollution (chemical, mechanical).

The assembly sequence evaluation index is calculated as the product of the q_a indicator of all the assembly connections appearing in the evaluated sequence. The assembly sequence including all the assembly connections is evaluated according to the Q indicator. This indicator is the sum n of the assembly connections existing in the sequence, and characterised by the value of the indicator equal to q_{an}. The lower the value of Q the better the assembly sequence. The minimum value of Q is $Q = n \cdot 1{,}0 = n \cdot q_{an-min}$, where n is the number of connections in the evaluated sequence, and where q_{an-min} is the smallest (the best) q_a indicator value for the connections n in the evaluated sequence and is equal to *1,0*.

2.3 Defining the constraints

Determination of the correct assembly sequences requires appropriate precedence constraints. They are related to the set of connections recorded in the M_k matrix. Each connection can be assigned to one of three designators:
– starting connections (p_s) - connections of two parts from which the creation of the assembly sequence variants of the product starts,
– connection 'skip' (p_p) - this connection is not taken into account when generating the assembly sequence variants of the product,
– blocking connection (p_b) - connection which prevents or limits getting a complete assembly in the later course of the assembly process.

The first type of constraints (starting connection) is used predominantly to define base components and parts from which the assembly sequence formation starts.

Connections of the 'skip' type are defined in the case of reduction of a generated feasible assembly sequences set. This constraint can help to exclude resulting sequences with unfavourable sub-sequences.

The last of the constraints, and the most important one, is blocking connection, which has a direct influence on generating the correct order of combining the parts, in terms of the selection completeness. This constraint is characteristic of those preceding connections, which prevent the realisation of the connection for which they are defined. This way the possibility of incorrect sequence when combining the parts is eliminated. It is assumed the blocking connections need to be defined with the operator 'and' ($\wedge$) and 'or' ($\vee$). In the first case, assigning the '$\wedge$'

operator to the blocking connections ($p_{b1} \wedge p_{b2} \wedge ... \wedge p_{bn}$) means that connection p_n, for which the blocking connections are defined, can be executed before every blocking connection is made. Thus, it is possible to make *n-1* blocking connections before the connection p_n, for which *n* blocking connections were defined. If all the blocking connections are executed, it is impossible to achieve complete assembly of the whole product because realisation of the connection p_n is blocked. In the second case, assigning the '$\vee$' operator to the blocking connections ($p_{b1} \vee p_{b2} \vee ... \vee p_{bn}$) means that connection p_n, for which the blocking connections are defined, has to be executed before any of them. Even if one of the blocking connections is made, it is impossible to achieve complete assembly of the whole product because realisation of the connection p_n is blocked. Furthermore, it is possible to define blocking connection sequences (with the '$\wedge$' operator) separating them by the use of the '$\vee$' operator.

2.4 Algorithm that produces feasible sequences

The proposed algorithm for determining and evaluating the assembly sequences allows generation of all permissible variants for assembly sequences with simultaneous evaluation.

In the algorithm three databases have been distinguished. The first of them contains data related to the product structure and relations between its components. Directly from the database – 1 a list of possible connections is created. The first step of the algorithm is to choose the first available connection from the starting connections list and create an assembly subsequence from its components. At the same time, when selecting a starting connection, its evaluation from the database - 2 is taken. This database contains information pertaining to evaluation of all the relations between the connections' components. This subsequence is recorded as the M_{K+1} matrix, which decreases the size of the M_K matrix by *1*. Relations recorded in the M_K matrix are changed into the form of the M_{K+1} matrix and constraints for the current subsequence are checked. All the constraints (connections of 'skip' type, blocking connections of 'OR' and 'AND' type) are recorded in the database 3. If there are any constraints, the current sequence is excluded from further consideration. If the constraints allow continuous building of the assembly sequence, more components are added. Subsequences of a higher order are created until a complete sequence meeting all the constraints is built. Produced sequences are then recorded and the starting connection used in the process is deleted from the list of available connections. Next, the algorithm chooses another available starting connection and the process of sequences creation is repeated. After every starting connection is used a set of all the possible assembly sequences is received.

3 Computer implementation of the method

The result of computer implementation of the method is EASYASSEMBLE program [11]. Four tabs of the program are presented in the **Figure 1**. In the first tab, *Structure Matrix*, the user defines relations between the parts and assigns their constituent values (h_p, f_p) of the grade indicator q_a. In the next tab, *Start Sequences*, the program generates the set of allowable operations out of which the user has the possibility of selecting the operations of “start” and “ignore” type (characteristics of these types of operations has been presented in part 1 of the article). In the *Blocking Sequences* tab, there are limitations of “OR” and/or “AND” type. All the information defined in the first three tabs is saved in a file with *.asp filename extension (abbreviation for assembly sequence planning). In the last tab, *Run Process*, an algorithm generating allowable assembly sequence according to previously defined *.asp file is performed.

The user has the possibility of reviewing the results and saving them to a text file (*.txt) as well as to obtain the information concerning particular steps of the algorithm.

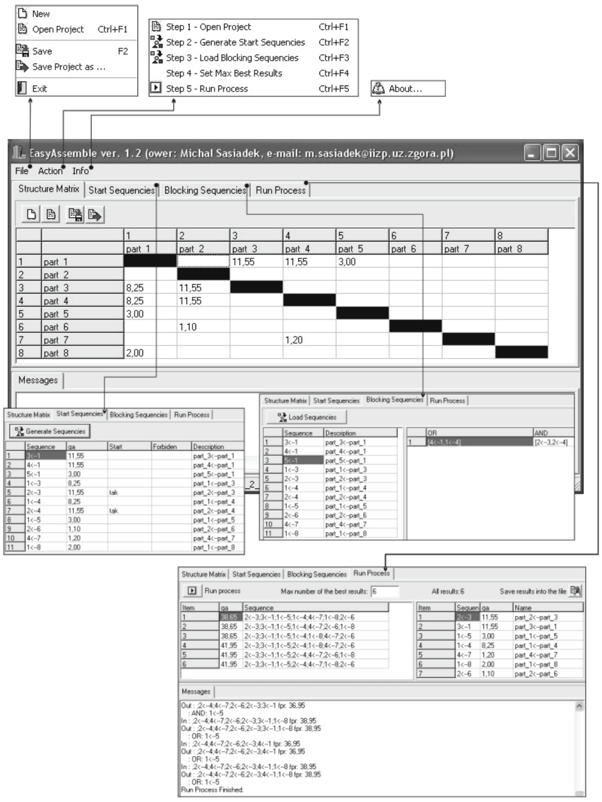


Fig. 1 The main dialog window of the EASYASSEMBLE program and its TabSheets

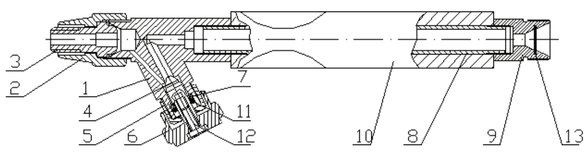


Fig. 2 Gas burner structure

4 EASYASSEMBLE method application

In this chapter the author presents an example of generating assembly sequences for a gas burner. On the basis of a generated set the best connection sequences of its components are shown. Moreover, an analysis of its structure aimed at simplifying the assembly is conducted. The structure of the gas burner is presented in **Figure 2**.

In the **Figure 3** indicates: 1 – Frame, 2-Screwed sleeve, 3-Jointing sleeve, 4-Valve, 5-Contract nut, 6-Valve knob, 7-Ring, 8-Handle's connector, 9-Connector's tip, 10-Handle, 11-O-ring, 12-Screw, 13-mesh.

The matrix of the structure of the analysed gas burner is presented in **Figure 3**. It includes all the possible connections between the component parts of the analysed product.

Basing on the matrix all the assembly connections which will be included in the sequence creation were defined and starting connections were designated. Furthermore, for every defined assembly connection there are conditions for constraints in the form of blocking connections OR and AND.

	1	2	3	4	5	6	7	8	9	10	11	12	13
1		X	X	X	X	X		X		X	X		
2	X		X										
3	X	X											
4	X					X	X				X	X	
5	X												
6	X			X								X	
7				X							X		
8	X								X	X			
9								X		X			X
10	X							X	X				
11	X			X			X						
12				X		X							
13									X				

Fig. 3 Matrix of dependencies between the component parts of the gas burner

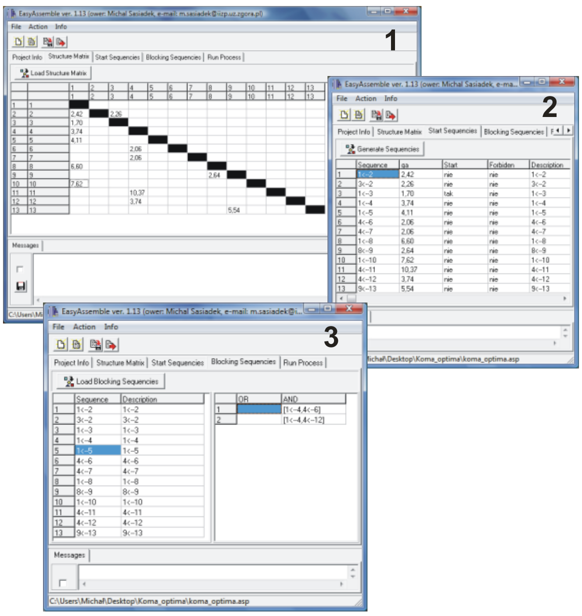


Fig. 4 Program's dialog boxes

In the next step, in order to evaluate the generated sequences, every defined assembly connection was assessed, according to the q_a indicator.

The consecutive steps of generating the set of permissible assembly sequences in the EASYASSEMBLE program are presented below. In three main dialog boxes (marked as 1, 2, 3) there are shown: the design structure record and evaluation of the assembly connections in the form of a matrix of the design structure, defining of the connections of 'start' and 'skip' type, defining of the constraints of 'and' and 'or' type (**Figure 4**).

In **Figure 5** the result dialog box of the program is shown. As a result of the algorithm's work 27720 sequences were obtained. The best evaluated sequences are:

– (1-4-7-11-5-6-12-8-10-9-13-3-2),
– (1-4-7-11-5-6-12-3-2-8-10-9-13).

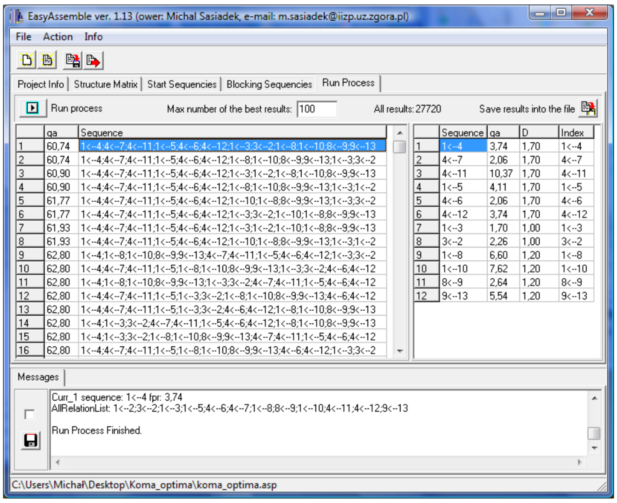


Fig. 5 Result dialog box for the gas burner

In these sequences the initial segment is the assembly of components 1, 4, 7, 11, 5, 6, 12 in this order and it results from the defined starting connection (1←4) and minimising the changes in the direction of joining subsequent components. In the following segments of both sequences evaluating of two subsequences takes place: (3-2) and (8-10-9-13).

4.1. DFA analysis of the gas burner structure

Another stage in the proposed method is an attempt to simplify the structure of the component parts of the product in order to reduce the value of the q_a indicator. The indicator encompasses basic rules of design for assembly methodology (DFA). Simplification of the structure should contribute also to greater efficiency of the assembly process. In the following four figures the propositions of changes are presented, along with their influence on the sequence evaluating.

The first change is to reduce the number of parts by redesigning the parts marked number 4 (valve) and 7 (ring) in the analysed gas burner. The ring serves to maintain the correct position of the O-ring in the frame, which guarantees sealing. Unfortunately, this solution is troublesome in terms of the assembly. The proposed change consists in designing a right socket in the valve, and placing the O-ring inside (**Figure 6**).

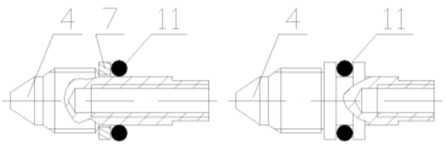


Fig. 6 Changes of the parts 4, 7, 11

Thanks to this solution the installation of the valve in the frame will be much easier because the valve and O-ring will make one subassembly installed in the frame, thus reducing the number of the installation operations performed previously.

The second proposed change is related to three parts: the handle's connector (8), handle's tip (9), and handle (10). The handle's connector originally had external threads of unequal length on both tips. This could cause an inaccurate fitting. If the connector was fitted in the frame the side with the shorter thread, the proper installation of the handle's tip (9) would be impossible. As a result, the handle's tip would not hold the handle (10) tightly enough. The proposed changes pertain to diversifying the threads on both sides of the connector. On one side it should be internal, on another external. This way the inappropriate fitting of the connector in the frame will be eliminated. The connector before and after changes is presented in **Figure 7**.

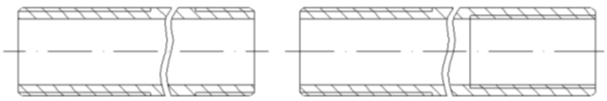


Fig. 7 Changes of the connector

The change in the connector structure involves redesigning of the connector's tip (9). This tip was redesigned to adjust it to the changed handle's connector. The thread was changed from internal to external, and the changes in the proposed construction are presented in **Figure 8**.

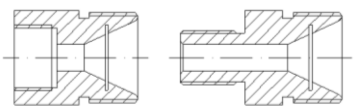


Fig. 8 Changes of the thread

The last proposed change is adjusting the structure of the handle so it would be impossible to fit it the wrong way round on the handle's connector, between the frame and the connector's tip. The proposed changes one more time relate to diversifying the handle's tips the way it would be explicit how to identify the sides of the proper installation. The designed handle from the side of the frame and connector does not differ in its structure, hence it is possible to fit it incorrectly because of its function. The handle would be fitted the other way round and would not be adjusted to the user's hand comfort. To eliminate the possibility of improper fitting the handle was redesigned by diversifying its shape on both tips and adapting its structure, on one side to the frame, on another to the connector (9). Moreover, diversification of the handle's tips will allow to eliminate the possibility of its incorrect installation. The handle before and after the changes is presented in **Figure 9**.

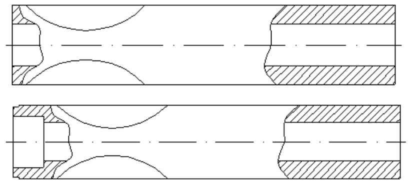


Fig. 9 Changes of the handle

As a result of the proposed changes one component part was reduced (ring no. 7) and alterations were introduced, which contributed to a decrease in the q_a indicator value of the connections with modified parts. Among others, the evaluation indicator of the connections 1←8 and 1←10 by changing the component value *A* from *2,5* to *1,0*. The number of the assembly connections was also reduced, from 13 to 11.

During another analysis of determining the best sequence a set of 10800 permissible assembly sequences for the redesigned gas burner was obtained. The best 20 solutions are presented in the result dialog box of the program, in **Figure 10**.

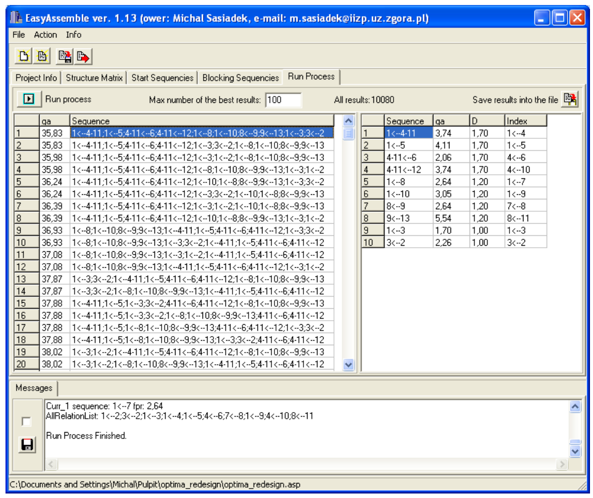


Fig. 10 Result dialog box for the redesigned gas burner

The best solutions are two sequences which have the evaluation indicator of *Q=35,83*. They are:

– 1-(4-11)-5-6-12-8-9-13-3-2,
– 1-(4-11)-5-6-12-3-2-8-9-13.

Parts 4 and 11 in brackets were first thought of as one subassembly, which is presented in **Figure 6**.

5 Summary and conclusions

Due to vital influence of the assembly work on the cost and quality of machines and mechanical devices, a constructor should have at his or her disposal an efficient tool for planning a proper assembly order and evaluating the designed structure in terms of the assembly requirements. He or she should have a chance to choose the best order of the assembly operations. Hence, the design for assembly should be included concurrently in the design process. This way it is easy to avoid structures which do not meet the assembly process requirements.

The article describes a method for determining the assembly sequences performed concurrently to a product's structure designing. It allows to adapt the structure (at the stage of early design) to requirements of the assembly process and to plan the assembly early during the product completion. The application of a developed computer program working on the main assumptions of the method is presented on a real example.

The EASYASSEMBLE computer program was used to designate the permissible assembly sequences for a gas burner consisting of 13 component parts.

On the basis of the results an analysis of the possibility of modification of the burner components' structure was conducted. It was meant to improve the value of the evaluation indicator for the particular assembly connections. Changes in the structure of five components were proposed: the valve (4), ring (7), connector (8), connector's tip (9), and handle (10). After including the changes the evaluation of the assembly connections was modified and a set of permissible assembly sequences was defined. Because of the proposed structure changes, the number of the component parts was reduced by one, also the evaluation q_a indicator was decreased for two assembly connections. Thanks to the introduced changes, the set of permissible sequences was reduced from 27720 to 10800. The achieved results are shown in **Figure 10**. It can be noted that evaluating of particular sequences was decreased, thus improved. The best sequence was generated for the starting connection 1←4 and the evaluation indicator value for this sequence is $q_a=35,83$.

In comparison to the results gained for the gas burner before the structure changes it should be noticed that better solution is to start the assembly from the valve side (4), which additionally, after the changes, is fitted as a subassembly with the O-ring (11).

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