

Automated Assembly Sequence Planning Based on 3D Assembly Model

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Abstract:-

Assembly sequence planning (ASP) plays an important role in the product design and manufacturing. A good assembly sequence can help to reduce the cost and time of the manufacturing process. This paper introduces a proposed methodology to generate assembly sequence planning based on assembly features and disassembly approach. The proposed methodology is completely implemented by designing an integrated system called ST-ASP system which is built by using Visual Basic 6.0 supported by Autodesk Mechanical Desktop 2009 Package and implemented on (HP Pavilion dv6) PC. The system directly extracts geometrical information from assembly model, generates assembly information which is represented by feasible assembly sequence plans, then finds the best assembly sequence plan based on assembly time required to generate each feasible assembly sequence. Finally the system has been tested to carry out a case study to demonstrate the feasibility of the proposed methodology.

Keywords: Assembly sequence planning, Assembly constraints, Assembly sequence generation, Assembly sequence evaluation, Interference matrix.

1. Introduction

Product assembly is a very important manufacturing activity. Assembly processes usually account for a significant percentage of total production time and total manufacturing cost. In traditional industrial manufacturing, assembly processes consume about 50% of total production time, and account for more than 20% of total manufacturing cost. Thus, to be competitive in today's market environment, manufacturers must strive continually to reduce assembly time and cost. To reduce overall assembly cost, manufacturers can reduce labor cost, the number of fixture and tool changes or the number of reorientations during an assembly process, and equipment operation cost [10].

Assembly sequence planning can help reduce overall manufacturing assembly time and cost by helping manufacturers reduce the number of fixture and tool changes or the number of reorientations during the assembly process. So, the objective of assembly planning is to find a feasible assembly sequence with the minimum assembly cost and assembly time. In addition, assembly sequence planning can play an important role in product design. During the design stage, designers can use assembly planning to verify that a design can be assembled safely without any interference or collision between components [4].

2. Assembly Planning

Assembly planning is commonly used to refer to the process of creating a detailed assembly plan to create the whole

(product) from separate parts, or is the process of preparing detailed sets of instructions to assemble a product. The instructions include the assembly tasks involved [1, 6, 11]:

1. **Fixture Planning:** A fixture planning determines the base component, the first component to assemble, and the fixtures.
2. **Feeding Planning:** A feeding planning determines the feeders for the components to assemble.
3. **Assembly Sequence Planning:** An assembly sequence planning determines feasible assembly sequences for a product.
4. **Stability Analysis:** A stability analysis checks whether an assembly is stable, and thus can be used as partial assembly or subassembly.
5. **Grip Planning:** A grip planning determines the tools for gripping a component, and the areas on the component where to grasp it.
6. **Motion Planning:** A motion planning determines a path for a component to be added to the partial assembly, from the feeding position to the final assembled position.

2.1 Assembly Sequence Planning

It is generally defined as the subset of assembly planning which only considers the ordering of part placement and the constraints required for definition [6]. There are many possible assembly sequences for each product. However, assembly operations cannot be implemented in a random order because some operations may prevent the execution of others owing to geometric or other constraints. The assembly constraints can be classified into two categories the hard constraints and soft constraints (operative constraints) [5].

1. Hard Constraints

Such as geometric and kinematic constraints, topological constraints, and stability constraints, these constraints are mainly related to the generation of assembly relations and used to check the feasibility of assembly operations. The hard constraints cannot be violated without affecting the sequence feasibility [19].

a. Geometric and kinematic constraints

They are related to product geometry, such as contact, or interference, or allowable position and orientation relations between two parts, between a part and a subassembly, or between two subassemblies and collision-free paths in an assembly. Geometric and kinematic constraints may be described by predicates such as interfere and geometry infeasible [5, 16]

b. Topological constraints

A topological constraint implies that the parts in an assembly are interconnected or that one part is connected through features with another part directly. Topological constraints may be described by predicates such as connect, coherent, not connect, and not coherent which are used in the assembly knowledge base [14].

c. Stability and security constraints

A subassembly is said to be stable and secured if its parts maintain their relative positions and do not spontaneously break contact. A subassembly has stability and security if it has zero degree of freedom for the relative motion of all parts in the subassembly and satisfies the constraints of fasteners (fastened) tightness or clearance mating. A subassembly not satisfying the stability or security constraints means that it is unstable

and changeable and is thus infeasible [14].

2. Soft constraints

They are made by assembly planners, related to the evaluation and selection of assembly relations or operations. The soft constraints may be derived from information such as part weight, part size, part complexity, part material and tool change [2]. Soft constraints can include, for example, maximum number of fixtures that can be used, maximum number of assembly operations that can be executed in parallel, and the choice of base part, although the soft constraints can be violated without resulting in part collision [17, 15, 9].

Assembly sequence planning typically comprises three major components:

1. Assembly sequence generation
2. Assembly sequence representation
3. Assembly sequence evaluation

The choice of an assembly sequence affects several functions such as [3]:

1. The difficulty of assembly steps.
2. The need for fixturing.
3. The changing of tools during assembly.
4. The potential for part damage during assembly.
5. The ability to do in-process testing.
6. The efficiency of the assembly process
7. Unit cost of assembly.

2.1.1 Assembly Sequence Generation

There are normally two ways to generate the assembly sequence(s). One is based on disassembly planning, which is also called decomposition, top-down, backward, or indirect planning method.

The other is based on assembly planning, which is also called construction, bottom-up, forward, or direct planning. The sequence of assembly of the former is then obtained as the reverse of the sequence of disassembly. Both assembly and disassembly planning requires some knowledge and reasoning method to generate assembly sequences. The knowledge could include interpreting the assembly drawing, and process and resource characteristics. The reasoning method could be based on geometric reasoning, constrained priority, rule-based, or case-based reasoning. The reasoning method could be implemented algorithmically. Techniques for assembly sequence generation can be roughly classified into the following categories: the algorithmic approach, the integrated approach, the knowledge based reasoning approach, and the Case Based Reasoning (CBR) approach [18, 12].

2.1.2 Assembly Sequence Representation

There are four main approaches for assembly sequence representation, lingual representation which is involved the use of a special language for representation of subassemblies, parts and the relations between them, Part and Assembly Description Language (PADL), Geometric Design Processor(GDP) and AUTOMated Parts Assembly System (AUTOPASS) are examples of this group, order list representation which is represented each assembly sequence by sets of lists, artificial intelligence based representation are rule based, heuristic search such as depth-first search, and breadth-first search, and graph based representation in which components are represented by nodes and relations between components are represented by edges such as AND/OR graph, state graph, and precedence graph [8,7,13].

2.1.3 Assembly Sequence Evaluation

A product may be large and contain many feasible assembly or disassembly sequences, although some hard and soft constraints are considered in the generation of the assembly sequence. There is need to develop appropriate procedures to reduce the sequence account, so that the optimal assembly sequence can be selected to meet the needs for a particular purpose within available resources. Several evaluation criteria have been proposed, some are related to the assembly sequence, and others take in account the characteristics of assembly system [17, 7].

Two major category factors are used as a selection and evaluation criteria, the qualitative factors and quantitative factors. One or more of the following important qualitative criteria are considered for the selection of sequences [19]:

1. Frequency of direction changes
2. Stability and security of subassemblies
3. Assembling fasteners
4. Type of assembly cell

5. Clustering of the parts
6. Reliability of the tasks

The quantitative characteristics may include the time required to accomplish the assembly tasks, cost of hardware, cost of fixturing or tooling to secure the unstable states, the factors to be considered may be as follows:

1. Total assembly time including subassembly operations time, transportation time.
2. Total assembly cost includes labor cost, fixturing and tooling cost
3. Number of product reorientations during assembly
4. Number of fixtures
5. Number of operators
6. Number of robot grippers
7. Insertion priority for specific part

3. Methodology

The proposed methodology to generate assembly sequence planning composed of three components: product representation, assembly features recognition, and assembly sequence planning as shown in the Fig. (1).

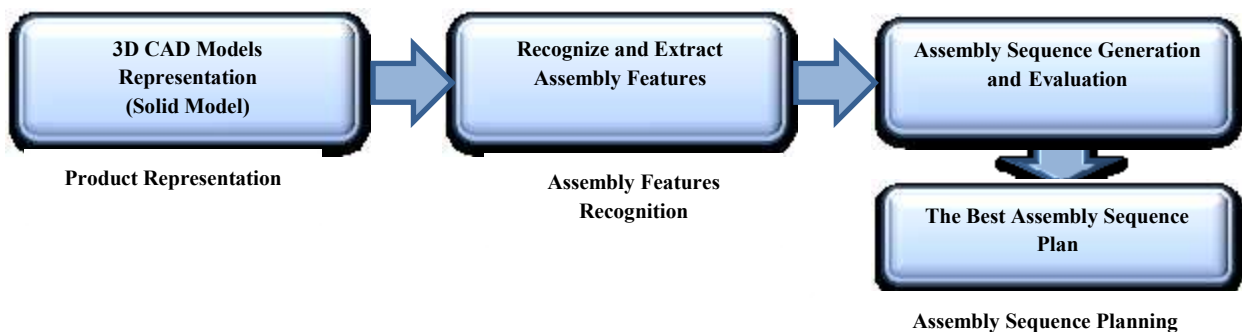


Fig. 1 Proposed Methodology Structure

3.1 Product Representation

In the first stage of the proposed methodology, the product parts are designed through CAD software and they are represented as solid models. The

designed parts can be represented by 2D drawing and then applying the extrude or revolve operations, or 3D drawing by using Constructive Solid Geometry (CSG) as a design tool in which the designed part

is constructed using the fixed set of solid primitives (block, cylinder, sphere, wedge, and torus) and a compound 3D solid model can be created by combining two or more solid primitives using the Boolean operations (union, subtraction, and intersection).

The CAD software generates and provides the geometrical information of the parts design in the form of STEP AP203 file that is then used as a standard format that provides the proposed methodology the ability to communicate with the different CAD/CAM systems.

3.2 Assembly Features Recognition

The geometrical and topological information of the designed parts are extracted from STEP AP203 file. The topological relationships between geometric entities of a CAD model are represented using Attribute Adjacency Graph (AAG) and Attribute Adjacency Matrix (AAM) to simplify the analysis of the geometric entities for form feature recognition. Assembly feature is recognized by matching pair of form features associated with assembly mating relations (e.g. against, fit, insert, align)". The matching between form features can be determined by examination of the form feature type and form feature Attribute Adjacency Matrix(AAM).

3.3 Assembly Sequence Planning

3.3.1 Assembly Sequence Generation

Assembly sequence planning can be generated based on "assembly by disassembling" approach in which an assembly sequence results from systematically disassembling the final product and reversing the disassembling sequence. At each level during the planning process, only one component is removed from the assembly. In this paper to generate assembly sequence plan, the

disassembly direction is determined which is the most frequently used in disassembly path generation and the result of completely disassembling a product is used to generate the precedence relationships between parts which is essential in assembly sequence generation.

In this paper the interference matrices are used and developed to generate automated disassembly sequence planning. Interference is occur when one component collides (obstructs) with another component during the movement for assembly (or disassembly). Component interference information is modeled as elements of interference matrices, three of these matrices which correspond to the positive directions of (+X, +Y and +Z), and three matrices to the negative direction of (-X, -Y, -Z).

By taking any two components in their final assembly position the I_{ij} Value shown in the matrix represents:

$$I_{ij} = \begin{cases} 1 & \text{If the component } i \\ & \text{interferes with the} \\ & \text{component } j \text{ during the} \\ & \text{disassembly} \\ & \text{movement} \\ 0 & \text{otherwise} \end{cases}$$

The diagonal element is put to zero, because the disassembly of a subassembly cannot be obstructed by itself.

According to interference matrix the product disassembly starts by checking the rows that contain "0" elements only, the selected row can be disassembled in the corresponding direction and this row represents the first part to be disassembly from assembled product. The matrix is reduced by removing the rows that contain (0) element and continuing in a similar way to complete the product disassembly. Fig. (2) illustrates the explosion view and the interference matrix of assembled product in + Y direction , and Fig. (3) illustrates the disassembly interference matrices of the product in + Y direction.

The disassembly of the product in Fig. (3) will be done as follows:

Firstly we delete the row (E) from the first matrix, this represents the first parts that are disassembled from the product, then row (D) will be deleted from the second matrix and so on until the last part is disassembled from the product which is considered the base part.

From the above disassembly approach, the assembly sequence will be generated by

reversing the disassembly sequence. The important constraints of the assembly plans are the precedence relationships between the parts. Thus feasible assembly plans must satisfy all precedence constraints. The precedence constraints can be represented by a directed graph. In this research the precedence constraints are determined from disassembly analysis.

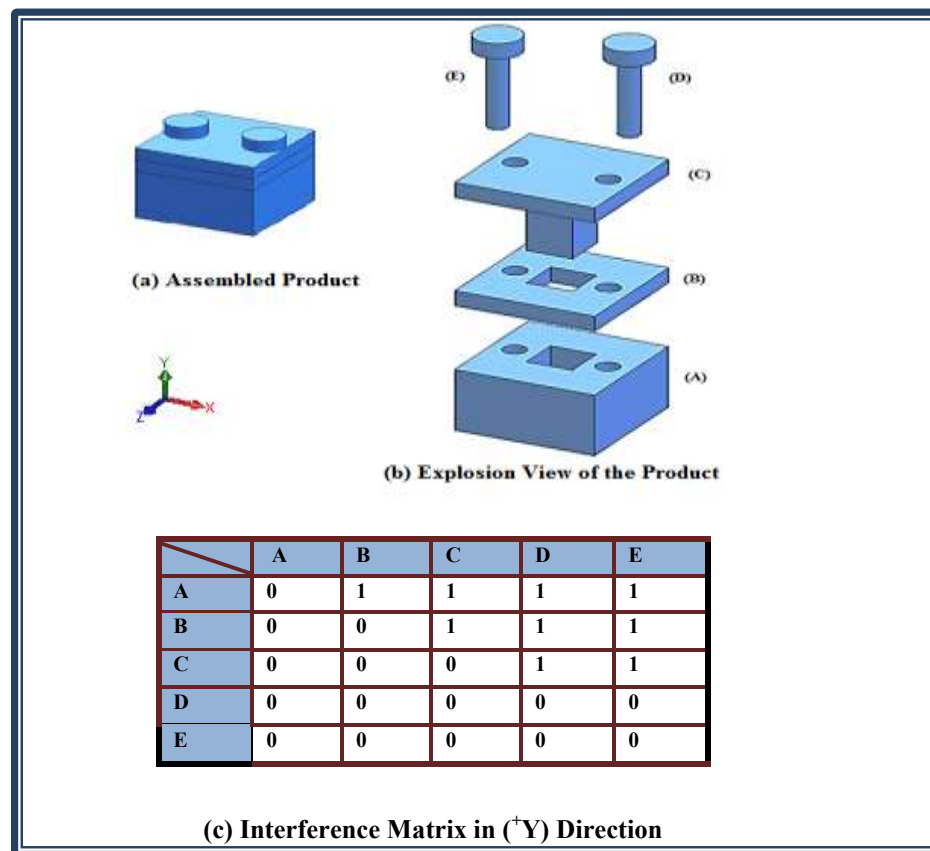


Fig. 2 Disassembly Interference Matrices of the Product in + Y direction (a) Assembled Product, (b) Explosion View of the Product, (c) Interference Matrix

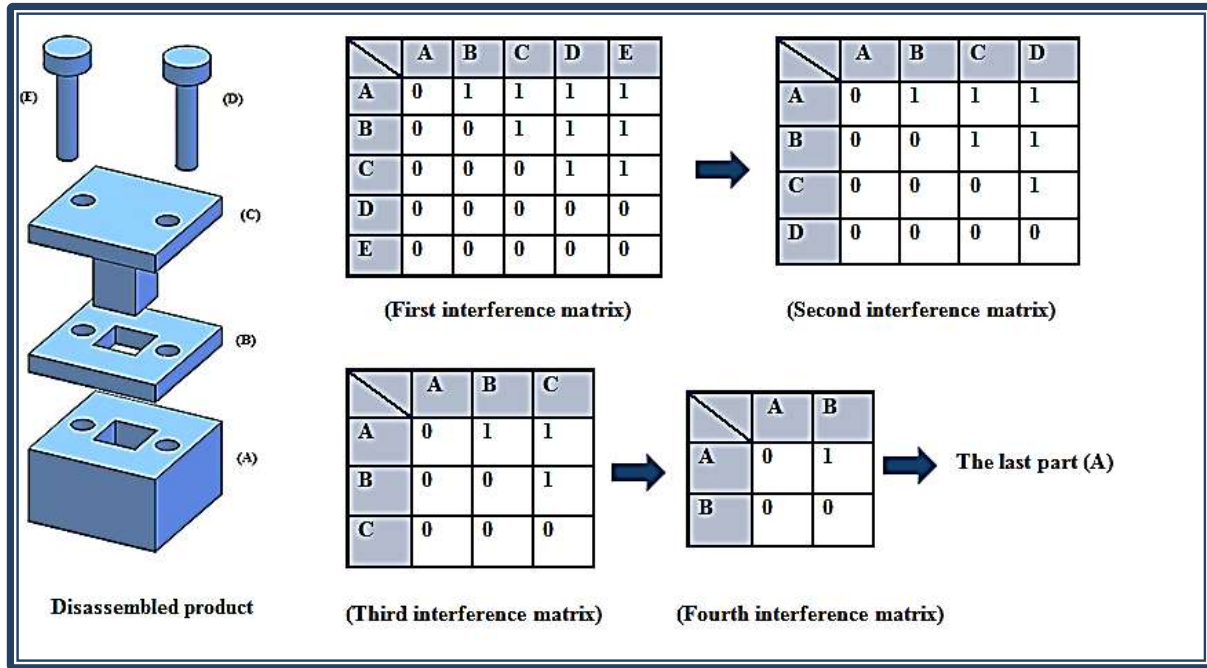


Fig. 3 Disassembly Interference Matrices of the Product

3.3.2 Assembly Sequence Evaluation

To save time and cost in assembly process and to improve the quality of products, it is very important to choose an optimal assembly sequence.

A basic requirement for a valid assembly sequence is a feasible sequence. An assembly sequence is said to be feasible if all the assembly tasks are geometrically feasible. A typical product can have hundreds or thousands of feasible assembly sequences, and this number increases when the number of parts increases. It is critical to use some methods to reduce the sequence count in order to select the optimal assembly sequence. With the assembly features and precedence constraint the size of search space of assembly planning is prominently decreased and assembly sequence of complex products can be generated efficiently.

According to the kind of product and assembly circumstances, the evaluation of assembly sequences requires various evaluation criteria such as assembly time, tools change, direction change, number of

reorientation, base part, etc. The criterion considered in this paper is assembly time.

Many factors have a significant impact on assembly time and play a major role in optimizing assembly sequences. Usually the assembly time can be determined based on the parts mating time, parts direction change time, parts handling time, tools change time, and jigs and fixtures change time. The parts mating time, and parts direction change time factors will be considered in this paper to obtain assembly time. Assembly time for each feasible sequence can be predicted using the following equation:

$$T_{\text{Assembly}} = \sum_{i=1}^n T_{mij} + \sum T_{Di}$$

where:

i: First part to be assembly (for i=1.....n)

j: Second part to be assembly (for j=1.....n)

T_{mij} : parts mating time

T_{Di} : Part direction change time (based on feature orientation)

Fig. 4 shows the flowchart of proposed algorithm for automated assembly sequence planning.

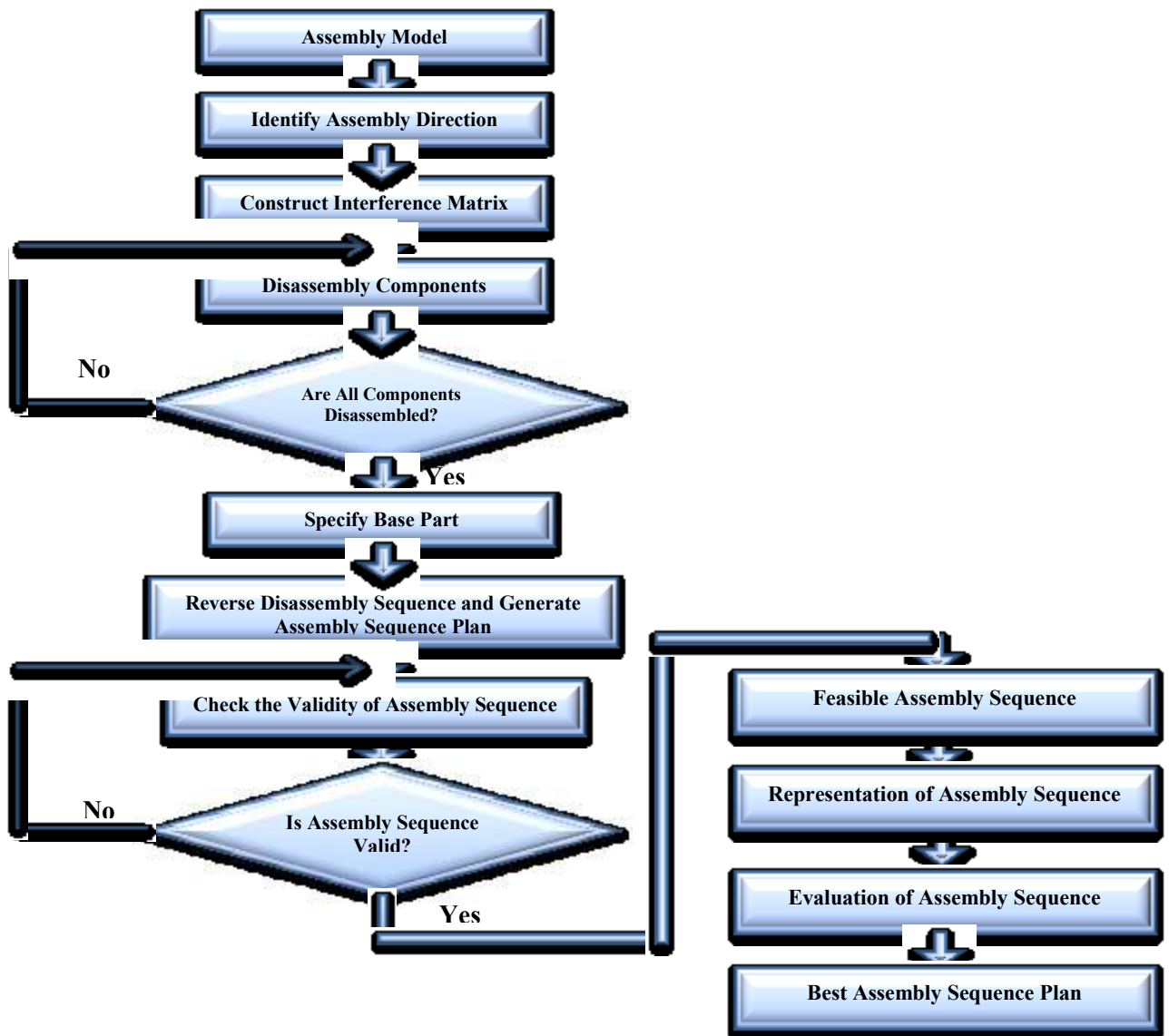


Fig. (4) Flowchart of Proposed Algorithm for Automated Assembly Sequence Planning

4. ST-ASP System Architecture

The developed STEP-based Assembly Sequence Planning (ST-ASP) system has the ability to extract the information from the product description; this information includes geometry, geometric relationships, and dimensions. The system has the ability to recognize features and extract the parameters of the features, and generate, represent, and evaluate the assembly sequences and produce the best one which consumes the lowest assembly time. ST-ASP system consists of three main modules: Design module, assembly feature module, and assembly planning

module. Through the design module the system links automatically with Autodesk Mechanical Desktop Package to drawing the mechanical parts and then save the designed parts as STEP AP203 file which represents the input to the assembly feature module. The assembly feature module consists of three sub modules; features data extraction which extracts the necessary information for features recognition from STEP file, form features recognition which is based on Attribute Adjacency Matrix (AAM) approach, and assembly features recognition which is based on matching form features and mating relations. Assembly planning module

consists of three sub modules; assembly sequence generation which is generates feasible assembly sequences for the final assembly model based on assembly information acquired from assembly features module, assembly sequence representation which is represent the feasible assembly sequences, and assembly sequence evaluation which is run the evaluation process by compute the total assembly time for each feasible assembly sequence and choice the sequence with the lowest time. Fig. (5) shows the architecture of ST-ASP system.

5. The ST-ASP System Testing

A case study is carried out and detailed to demonstrate the feasibility of the proposed methodology and the capability of the ST-ASP system. Fig. (6) shows ST-ASP system main window; Fig. (7) shows case study designed by Autodesk Mechanical Desktop package, Fig. (8) The Main Input to the Assembly Features Window, Fig. (9) shows the output result from assembly features recognition command, and Figs (10), (11), (12) show the outputs result from assembly planning module.

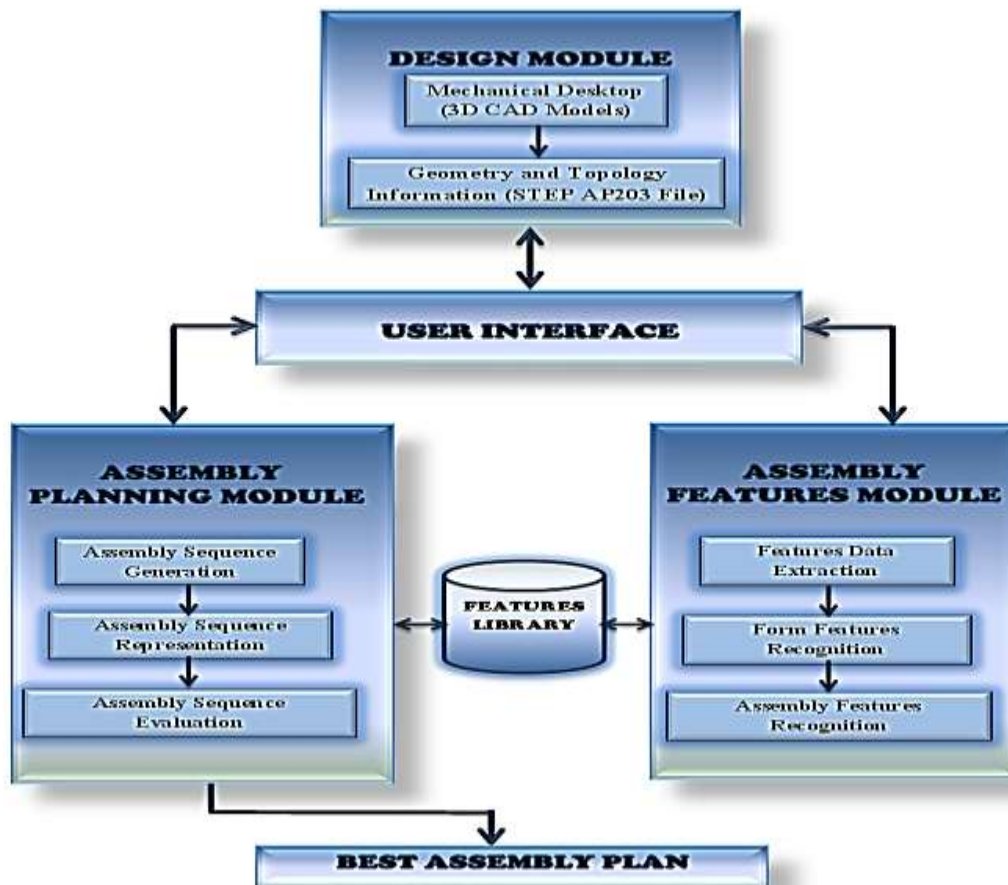


Fig. 5 Architecture of ST-ASP System

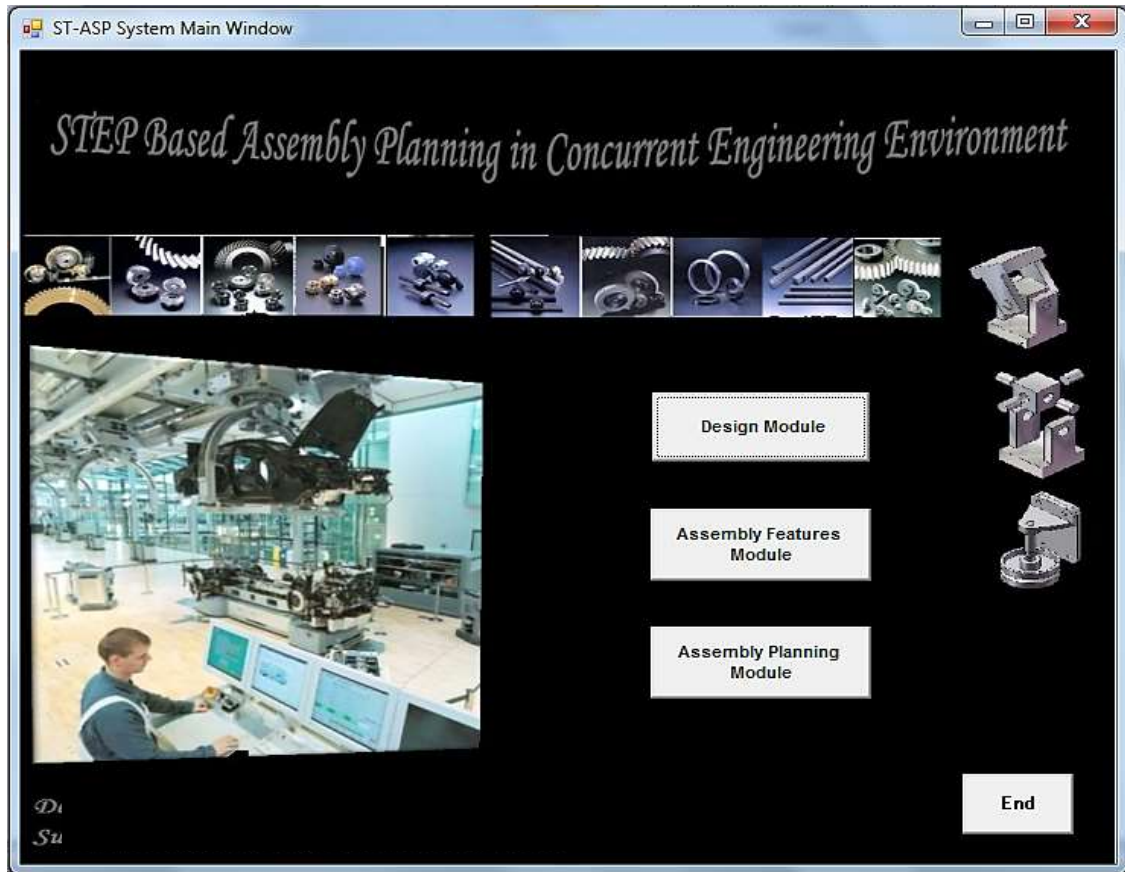


Fig. 6 ST-ASP Main Window

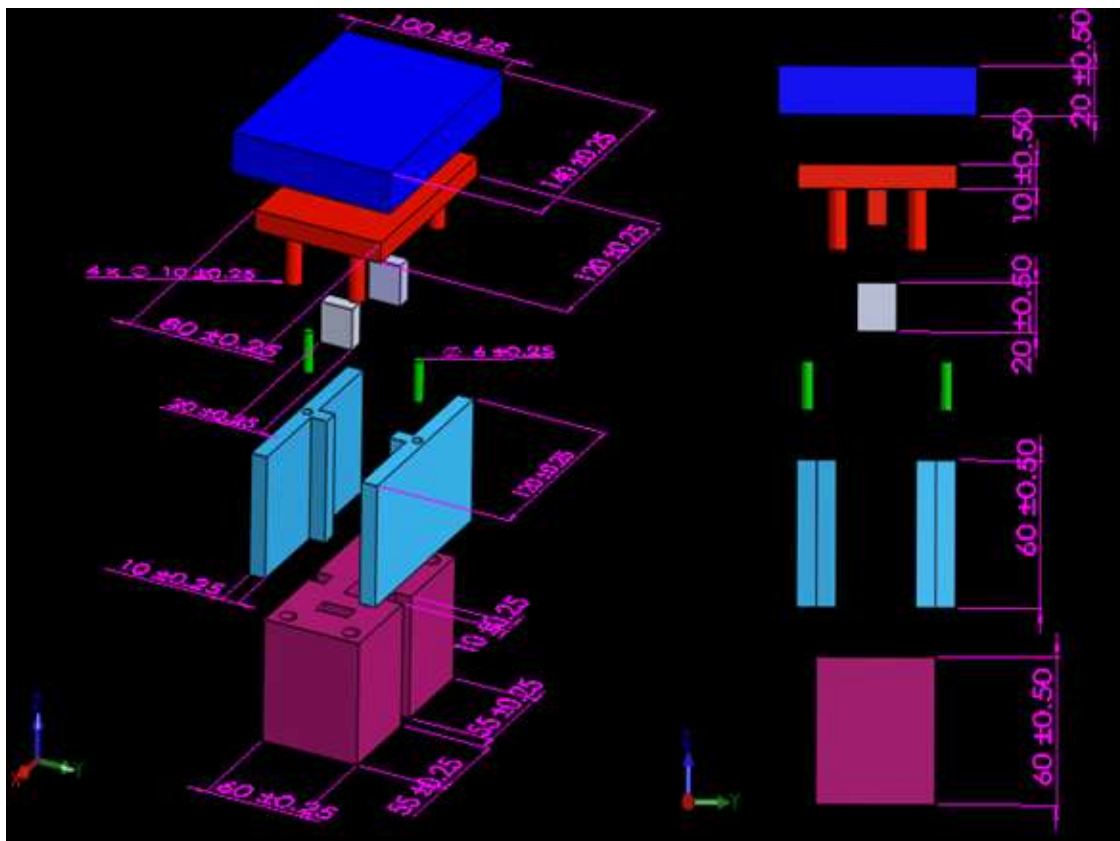


Fig. 7 3D CAD Models of Case Study

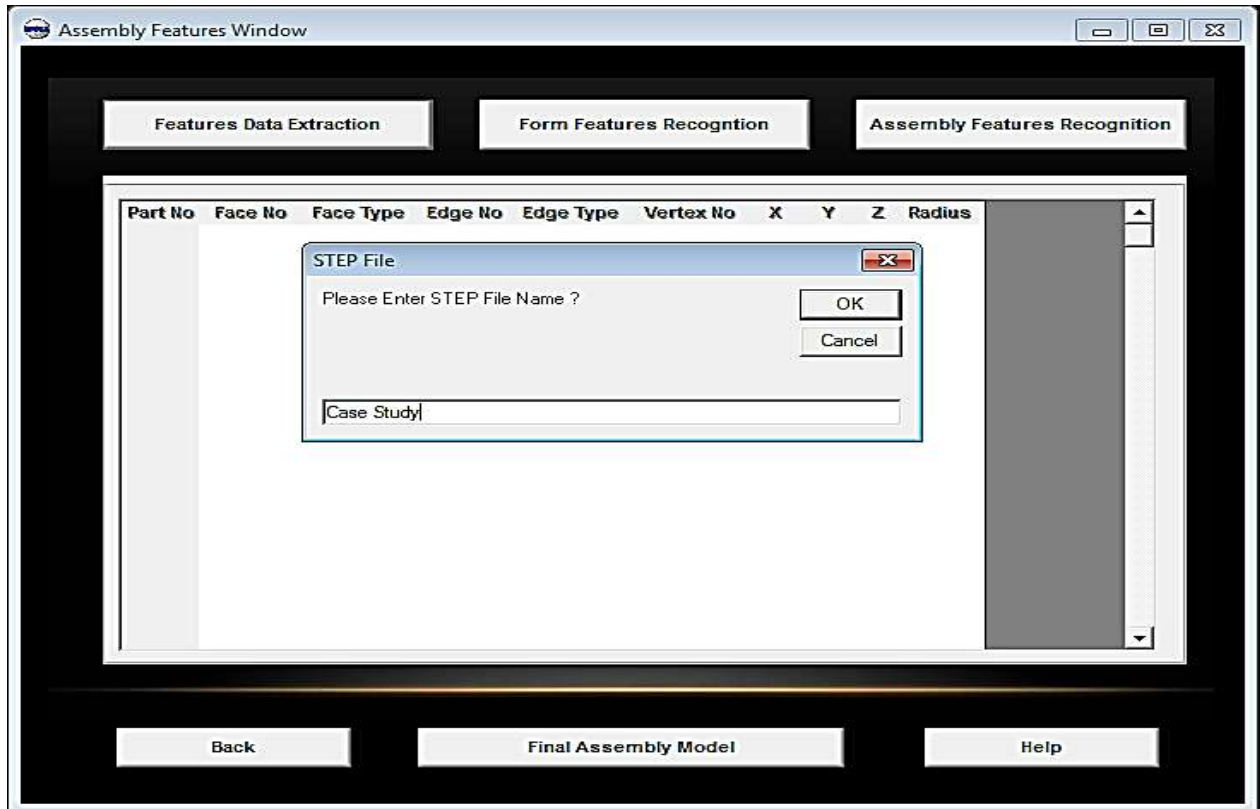


Fig. 8 The Main Input to the Assembly Features Window

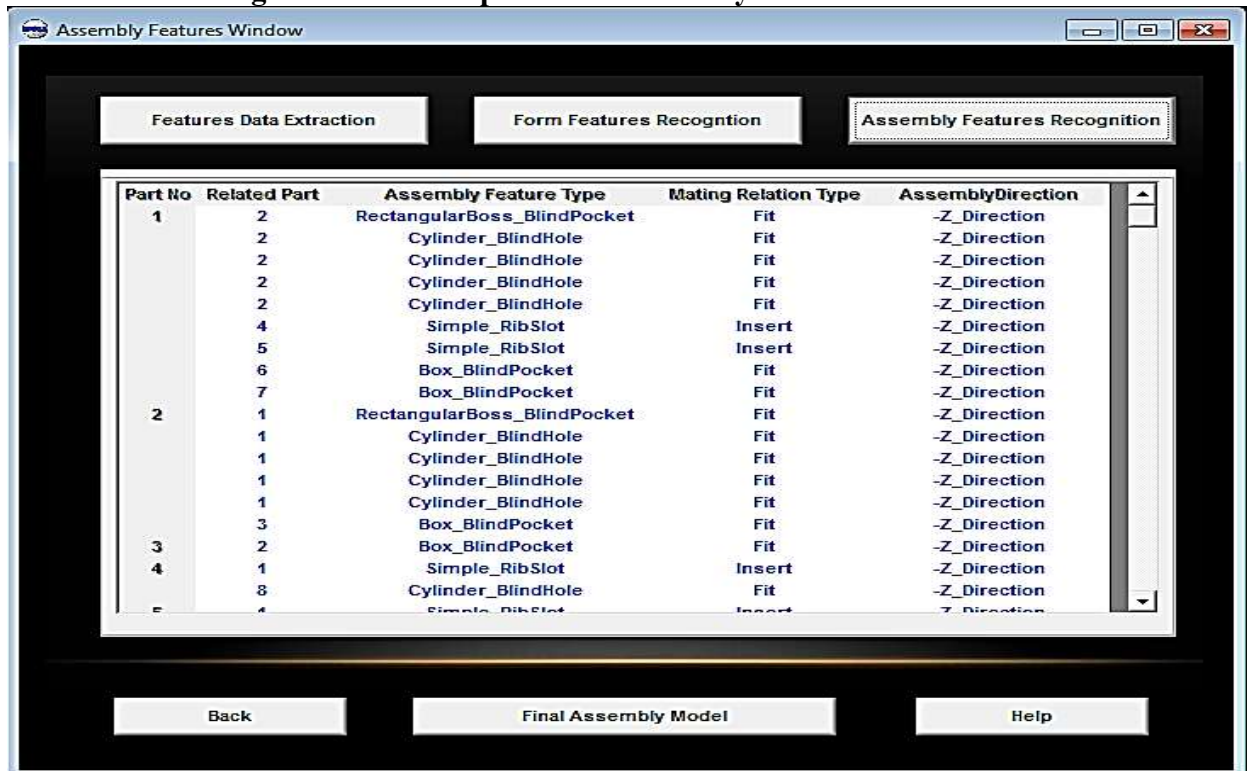


Fig. 9 Assembly Features Recognition Output

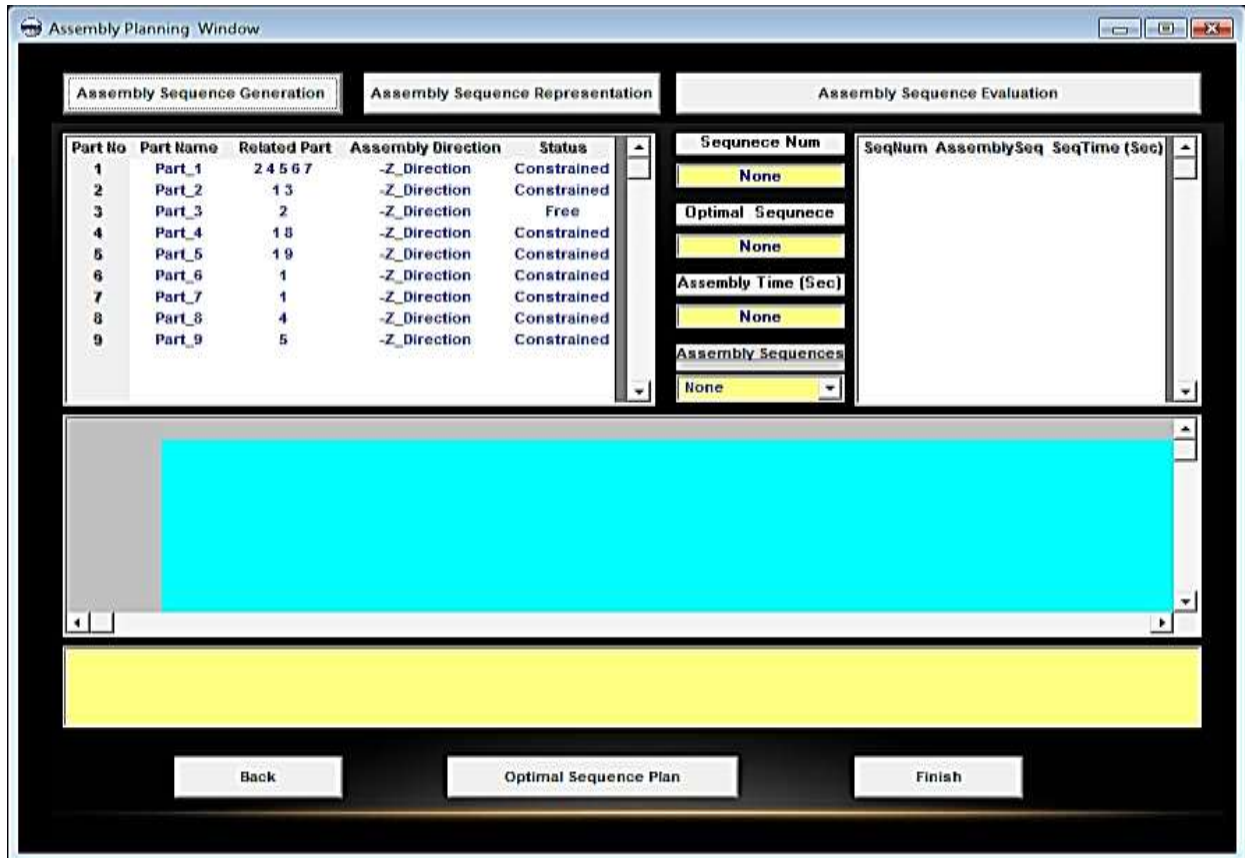


Fig. 10 Assembly Sequence Generation Output

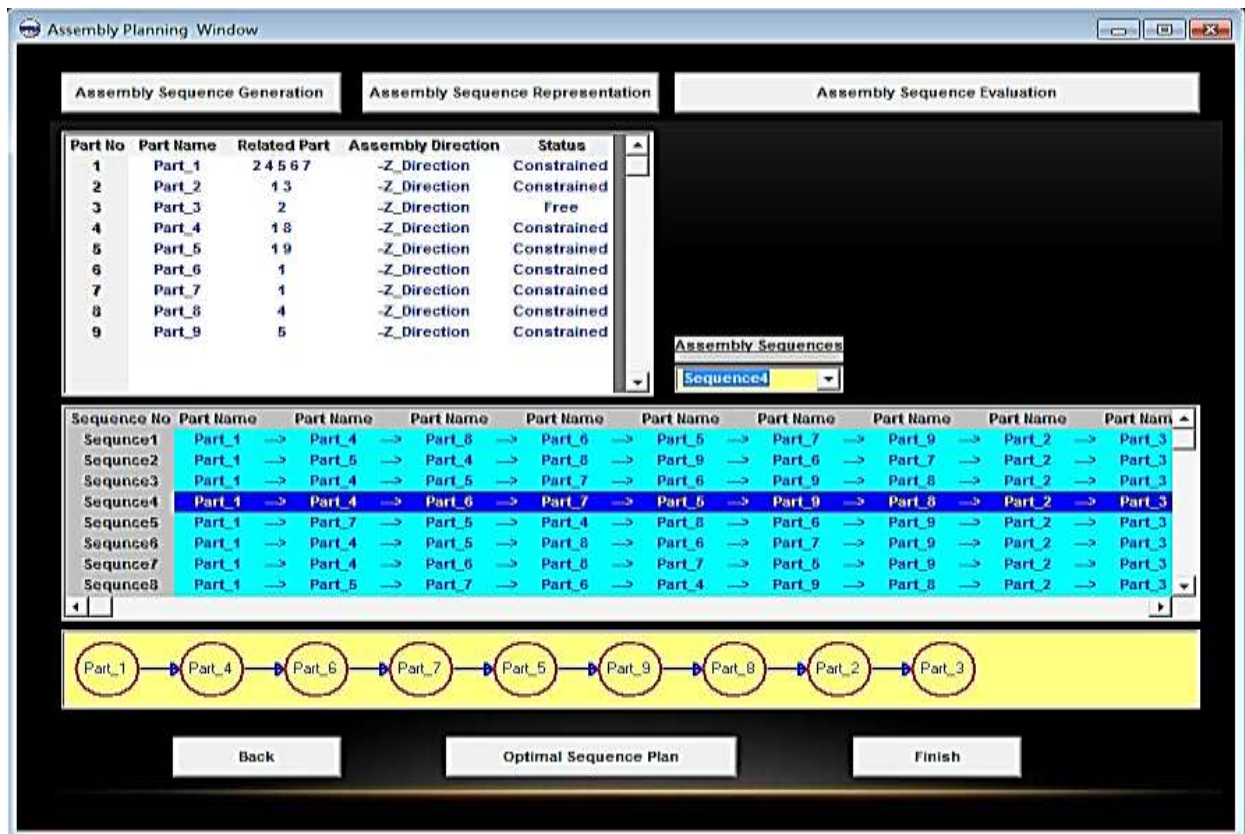


Fig. 11 Assembly Sequence Representation Output

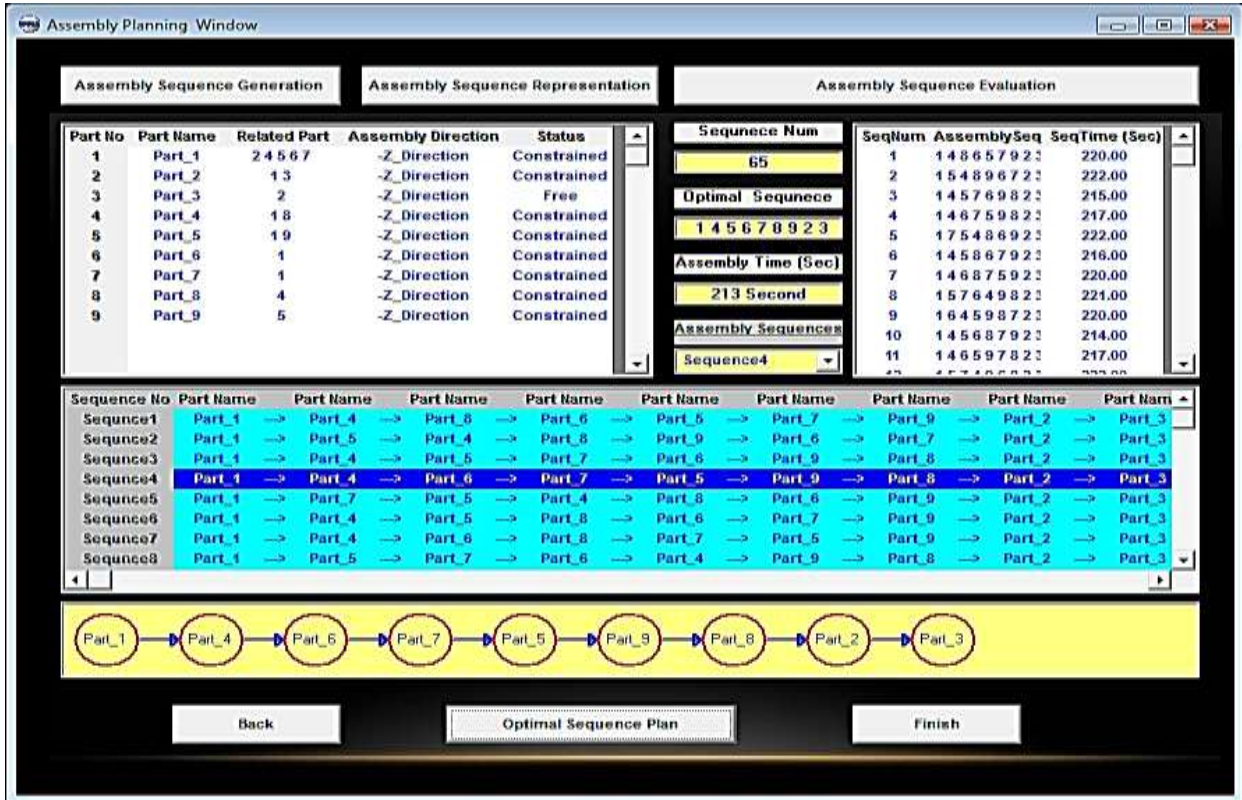


Fig. 12 Assembly Sequence Evaluation Output

6. Conclusion

The main contributions of this research include building a simple methodology for automated the generation of assembly sequence plans from assembly model. The use of assembly features and geometric reasoning based upon spatial constraint relationships among all parts in an assembly model decrease the number of the generated assembly sequences which is can be large even at a small parts count and can rise with increasing parts count. The proposed assembly planning algorithm determines the base part which is representing the first part of assembly sequence process and helps in reducing the complexity of the assembly sequence generation process. The ST-ASP system succeeded in achieving the integration between design and assembly planning and generates 180 feasible assembly sequences for the tested case study as shown in Appendix, and determining the assembly sequence (65) as the best assembly

sequence plan for the designed product which is requires (213 seconds) to assemble the product. The implementation of the system is considered easy in application and allows the user to save the output results in certain files.

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تخطيط تتابع التجميع المؤتمت بأعداد نموذج التجميع ثلاثي الأبعاد

الخلاصة

تخطيط تتابع التجميع يلعب دورا مهما في تصميم وتصنيع المنتج. تتابع التجميع الجيد ممكن ان يساعد في تقليل وقت وكلفة عملية التصنيع. هذا البحث يعرض منهجية مقترحة لتوليد تخطيط تتابع التجميع بالاعتماد على السمات التجميعية واسلوب التفكير. المنهجية المقترحة في هذا البحث تم تنفيذها بالكامل بواسطة تصميم نظام متكامل يدعى (ST-ASP), نظام (ST-ASP) تم تطويره باستخدام (Visual Basic 6.0) وبرنامج (Autodesk Mechanical Desktop 2009). النظام يستخرج المعلومات الهندسية من نموذج التجميع, يولد معلومات التجميع المتمثلة بخطت تتابع التجميع المجدية, ثم يجد افضل خطة تتابع تجميع بالاعتماد على الوقت اللازم لتوليد كل تتابع تجميع مجدي. اخيرا تم اختبار النظام على منتج ميكانيكي افتراضي لاستعراض جدوى المنهجية المقترحة.

الكلمات المرشدة: تخطيط تتابع التجميع, قيود التجميع, توليد تتابع التجميع, تقييم تتابع التجميع, مصفوفة التداخل.

(Appendix)

Assembly Sequence Plans Generated by ST-ASP System

| Sequence Number | Assembly Sequence | Sequence Time (Sec) |
|-----------------|-------------------|---------------------|
| 1 | 1 4 8 6 5 7 9 2 3 | 220 |
| 2 | 1 5 4 8 9 6 7 2 3 | 222 |
| 3 | 1 4 5 7 6 9 8 2 3 | 215 |
| 4 | 1 4 6 7 5 9 8 2 3 | 217 |
| 5 | 1 7 5 4 8 6 9 2 3 | 222 |
| 6 | 1 4 5 8 6 7 9 2 3 | 216 |
| 7 | 1 4 6 8 7 5 9 2 3 | 220 |
| 8 | 1 5 7 6 4 9 8 2 3 | 221 |
| 9 | 1 6 4 5 9 8 7 2 3 | 220 |
| 10 | 1 4 5 6 8 7 9 2 3 | 214 |
| 11 | 1 4 6 5 9 7 8 2 3 | 217 |
| 12 | 1 5 7 4 9 6 8 2 3 | 222 |
| 13 | 1 7 6 4 5 9 8 2 3 | 223 |
| 14 | 1 6 7 5 4 9 8 2 3 | 223 |
| 15 | 1 7 4 5 9 6 8 2 3 | 223 |
| 16 | 1 6 5 4 7 8 9 2 3 | 217 |
| 17 | 1 4 7 6 5 8 9 2 3 | 217 |
| 18 | 1 6 7 4 5 9 8 2 3 | 222 |
| 19 | 1 4 8 7 5 9 6 2 3 | 225 |
| 20 | 1 4 5 9 6 7 8 2 3 | 219 |
| 21 | 1 4 8 6 5 9 7 2 3 | 222 |
| 22 | 1 7 4 6 5 9 8 2 3 | 221 |

| | | |
|----|-------------------|-----|
| 23 | 1 5 9 6 4 7 8 2 3 | 227 |
| 24 | 1 4 8 7 6 5 9 2 3 | 223 |
| 25 | 1 4 5 7 8 9 6 2 3 | 219 |
| 26 | 1 5 4 7 9 6 8 2 3 | 219 |
| 27 | 1 5 7 6 9 4 8 2 3 | 226 |
| 28 | 1 6 5 7 4 8 9 2 3 | 220 |
| 29 | 1 4 6 8 5 7 9 2 3 | 218 |
| 30 | 1 5 4 8 7 6 9 2 3 | 218 |
| 31 | 1 7 6 5 4 9 8 2 3 | 224 |
| 32 | 1 6 7 4 5 8 9 2 3 | 221 |
| 33 | 1 4 6 5 8 7 9 2 3 | 215 |
| 34 | 1 5 7 4 9 8 6 2 3 | 224 |
| 35 | 1 4 5 6 9 8 7 2 3 | 217 |
| 36 | 1 4 7 5 8 9 6 2 3 | 221 |
| 37 | 1 6 4 5 8 9 7 2 3 | 219 |
| 38 | 1 7 6 5 9 4 8 2 3 | 229 |
| 39 | 1 4 6 5 8 9 7 2 3 | 217 |
| 40 | 1 6 4 8 5 9 7 2 3 | 222 |
| 41 | 1 6 4 5 7 9 8 2 3 | 217 |
| 42 | 1 5 9 7 4 8 6 2 3 | 231 |
| 43 | 1 5 9 4 6 8 7 2 3 | 226 |
| 44 | 1 4 7 5 6 8 9 2 3 | 216 |
| 45 | 1 4 5 6 7 9 8 2 3 | 214 |
| 46 | 1 4 7 6 8 5 9 2 3 | 220 |
| 47 | 1 5 6 9 4 7 8 2 3 | 224 |
| 48 | 1 4 5 8 9 6 7 2 3 | 221 |
| 49 | 1 5 9 4 7 6 8 2 3 | 226 |
| 50 | 1 4 5 8 7 9 6 2 3 | 220 |
| 51 | 1 7 4 6 8 5 9 2 3 | 223 |
| 52 | 1 5 4 8 9 7 6 2 3 | 223 |
| 53 | 1 4 8 5 7 6 9 2 3 | 220 |
| 54 | 1 7 5 6 4 8 9 2 3 | 222 |
| 55 | 1 4 5 6 8 9 7 2 3 | 216 |
| 56 | 1 5 9 4 8 7 6 2 3 | 229 |
| 57 | 1 4 8 5 7 9 6 2 3 | 223 |
| 58 | 1 6 7 4 8 5 9 2 3 | 224 |

| | | |
|----|-------------------|-----|
| 59 | 1 7 4 6 5 8 9 2 3 | 220 |
| 60 | 1 5 9 7 4 6 8 2 3 | 229 |
| 61 | 1 7 5 9 4 6 8 2 3 | 229 |
| 62 | 1 4 7 5 6 9 8 2 3 | 217 |
| 63 | 1 4 5 7 6 8 9 2 3 | 214 |
| 64 | 1 5 4 9 6 8 7 2 3 | 221 |
| 65 | 1 4 5 6 7 8 9 2 3 | 213 |
| 66 | 1 7 4 8 6 5 9 2 3 | 225 |
| 67 | 1 5 6 4 7 8 9 2 3 | 216 |
| 68 | 1 4 7 8 5 9 6 2 3 | 224 |
| 69 | 1 4 5 9 8 7 6 2 3 | 223 |
| 70 | 1 4 5 8 9 7 6 2 3 | 222 |
| 71 | 1 5 7 9 4 8 6 2 3 | 229 |
| 72 | 1 4 7 5 9 8 6 2 3 | 222 |
| 73 | 1 4 5 9 7 8 6 2 3 | 222 |
| 74 | 1 6 5 4 9 8 7 2 3 | 221 |
| 75 | 1 5 6 7 4 9 8 2 3 | 220 |
| 76 | 1 5 4 6 8 9 7 2 3 | 217 |
| 77 | 1 5 4 6 9 8 7 2 3 | 218 |
| 78 | 1 5 4 9 7 6 8 2 3 | 221 |
| 79 | 1 5 9 7 6 4 8 2 3 | 231 |
| 80 | 1 5 4 8 6 7 9 2 3 | 217 |
| 81 | 1 4 5 7 9 8 6 2 3 | 220 |
| 82 | 1 4 6 7 5 8 9 2 3 | 216 |
| 83 | 1 6 5 4 8 7 9 2 3 | 218 |
| 84 | 1 7 4 5 9 8 6 2 3 | 225 |
| 85 | 1 4 8 7 5 6 9 2 3 | 222 |
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