OPTIMAL ASSEMBLY SEQUENCE PLANNING TOWARDS DESIGN FOR ASSEMBLY USING SIMULATED ANNEALING TECHNIQUE

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Abstract

Recent development in Design For Assembly (DFA) has motivated product designers towards minimizing the number of parts in a product so as to reduce the assembly efforts. Assembly sequence for the reduced number of parts with the modified part topologies may not be possible. Determination of optimal assembly sequence for the modified product by performing assembly sequence planning is highly time consuming and it demands high skilled user intervention. Assembly sequence planning is one of the multi objective optimization problem with multiple assembly constraints and huge search space. In order to achieve the optimum feasible assembly sequence with less computational time, researchers in the past proposed many methods. In this paper, an attempt is made to generate optimal feasible assembly sequences using DFA concept by considering all the assembly sequence testing criteria from obtained feasible assembly sequences. A simulated annealing technique is used to generate all sets of feasible assembly sequences. The obtained sequences consist n-1 levels during assembly, which will be reduced by DFA concept. DFA uses functionality of the assembled parts, material of the assembled parts and liaison data of the parts to reduce the number of levels of the assembly by considering the directional changes as the objective function.

Key words: Design for Assembly, Assembly sequence planning, Simulated annealing, Multi-objective optimization.

1. Introduction

DFA plays a key role in manufacturing industry to minimize assembly cost by optimizing the assembly process and to reduce the number of parts during assembly [1-2]. DFA simplifies the design and reduces the number of parts in the assembly because assembly is one of the major cost contribution operation in the manufacturing industry. To overcome this problem, researchers have worked towards implementation of knowledge based methods. As these methods consume lot of computational time due to huge search space for products with more number of parts [3-5], researchers focused on Artificial intelligent (AI) techniques to avoid huge search space problem. Though these approaches are successful to certain extent the major limitation with these approaches is local optimal solution.

In most of the AI techniques, the input supplied to the process is generated manually, which is also time consuming. Hence computer aided methods have been evolved to extract such information through various Computer Aided Design (CAD) exchanging data formats [6-11]. Graphical methods are used for testing the geometrical feasibility in the early stages. These methods, advanced CAD based assembly attribute extraction is used to reduce the human error and minimize the computational time.

Besides liaison and geometrical feasibility predicates, stability and mechanical feasibility are two essential assembly predicates to yield the appropriate results. The computer aided extraction of stability was discussed by several researchers [12-14]. Some AI techniques applied to achieve optimal assembly sequences are listed in table 1.

Table 1. Assembly predicates consideration in the cited research literature

Reference	Algorithm	Objective function (Minimization of)	Predicate criteria considered	Limitations
Smith et.at [15]	GA	Computational time	Liaison, Geometrical & Stability criteria are considered	Complexity in achieving global optima solution
Chen et.at [16]		Energy	Liaison & Geometrical criteria are considered	Local optimum solution
Chang et.at [17]	AIS	Assembly cost	Liaison & Geometrical criteria are considered	Complexity in achieving global optima solution
Deepak et.at [18]		Computational time	Liaison, Geometrical & Stability criteria are considered	Complexity in achieving global optima solution
Biswal et.at [19]	PSO	Directional changes	Liaison & Geometrical criteria are considered	Complexity in achieving global optima solution
Bahubalendruni et.at [20]		Directional changes	Liaison, Geometrical & Stability criteria are considered	Local optimum solution
Milner et.at [21]	SA	Assembly cost	Liaison & Geometrical criteria are considered	Complexity in achieving global optima solution
Motavalli, S [22]		Computational time	Liaison & Geometrical criteria are considered	Local optimum solution
Hong, D.S [23,24]		Energy	Liaison, Geometrical & Stability criteria are considered	Complexity in achieving global optima solution
Nayak et.at [25]		Assembly directional changes	Liaison & Geometrical criteria are considered	High execution time

Note: PSO-Particle Swarm Optimization, GA-Genetic Algorithm, AIS- Artificial Immune System, SA- Simulated Annealing

In this paper a SA algorithm along with CAD integration for extraction of liaison data, stability feasibility, mechanical feasibility and geometrical feasibility is used to achieve all set of feasible assembly sequences. DFA concept is applied to obtain the optimum feasible assembly sequence by reducing the number of levels of the assembly.

2. Assembly Sequence Validation and Assembly Information Extraction

Generally, required input data which generates manually for implementing the algorithm to obtain optimize feasible assembly sequence is a time consuming process. This section details about the methods to extract liaison matrix, interference matrices, stability matrix and mechanical feasibility matrix from CAD environment. Computer Aided Three-dimensional Interactive Application Version-5 (CATIA V5R17) is used as CAD tool and programming is done in VB (Visual Basic) scripting to extract the outcomes. A gear assembly structure consists of 9 parts is considered in this investigation as shown in the Fig. 1. The directions for assembly are given as 1: +x, 2: -x, 3: +y, 4: -y, 5: +z, 6: -z.

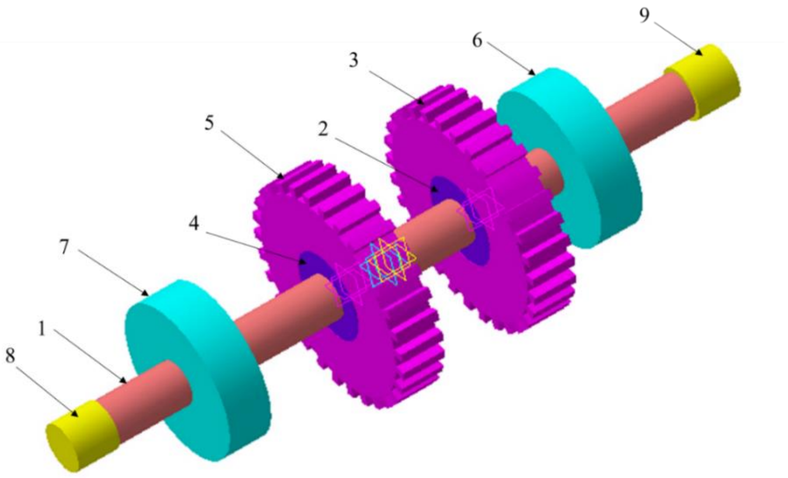

Fig. 1: A hypothetical assembly.

1- Shaft, 2 &4- Bearings, 3&5- Gears, 6&7- Rotating discs, 8&9- Nut

2.1. Liaison extraction

Liaison data gives the information about all possible mating surfaces of an assembly. Weights 0 &1 are assigned for the no mating and mating parts respectively. Since in the current investigation a nine-part assembly structure has been considered, a matrix of size 9X9 is extracted from the CAD tool-CATIA (V5R17). The obtained liaison matrix for the considered nine-part mechanical assembly structure is as follows:

$$\text{Liaison matrix} = \begin{array}{c|ccccccccc|} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 6 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

2.2. Interference matrix

The interference matrices provide the information about all possible interferences of the components during the assembly operations in the real environment. Weights 0 &1 are assigned for the interference and no interference respectively. Part movements during the assembly process are in six directions. Six interference matrices corresponding to each direction are obtained. Six matrices of 9X9 size are extracted from the CAD tool-CATIA (V5R17).

The obtained interference matrices for the considered nine-part mechanical assembly structure in +X and -X directions are obtained as follows:

+X

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
3 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
4 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
5 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
6 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\
7 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
8 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
9 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{array}$$

-X

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
3 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
4 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
5 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
6 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\
7 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
8 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
9 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{array}$$

The interference matrices along the positive and negative Y axes are obtained as follows:

+Y

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
2 & 1 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\
3 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
4 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\
5 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\
6 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\
7 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
8 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
9 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{array}$$

-Y

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
2 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\
3 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\
4 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\
5 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\
6 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
7 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \\
8 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
9 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0
\end{array}$$

The interference matrices along the positive and negative Z axes are obtained as follows:

+Z

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
3 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
4 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
5 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
6 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\
7 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
8 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
9 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{array}$$

- Z

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
3 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
4 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
5 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
6 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\
7 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
8 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
9 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{array}$$

2.3 Stability matrix

Stability matrix gives the information about the stability of the parts during assembly. The matrix represents the information about the parts which are incomplete stable, partial stable and complete stable. In this study three weights, 0, 1 & 2 have been allotted for incomplete stable, partial stable and complete stable assemblies respectively. A matrix of size 9X9 is extracted from the CAD tool-CATIA (V5R17).

$$\begin{array}{c|ccccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 2 & 2 \\
2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
4 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
6 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
7 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
8 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
9 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}$$

Combined stability matrix

2.4 Mechanical feasibility matrix

Mechanical feasibility is true for an assembly sequence when the assembly tools can perform the specified assembly operation without any collision; hence it is dependent on tools and methods used to perform the assembly operations. The hard connectors trajectory constraints can be represented through a three dimensional matrix of nxnxn. The third dimension represents, whether the part represented in it offers any interference to place hard connections between parts represented in first two dimensions. Since, there is no requirement of the mechanical feasibility matrix because absence of physical connectors.

In this paper, directional changes have been considered as the objective function to reduce the cost of the assembly. The directional change is represented as (D_C)

3. Simulated Annealing

Simulated annealing technique is taken from the mechanical annealing process. In this process, metal is heated to higher temperatures (i.e. recrystallization temperature) and allow the metal to cool slowly at room temperature so that mechanical properties of the metal increases.

Simulated annealing technique is used to generate all set of feasible assembly sequences by testing all the predicate criteria. In SA, a random assembly sequence is generated based on the higher temperature and lower temperature limits. The generated assembly sequence will be tested for liaison predicate, geometrical feasibility predicate, stability predicate and mechanical feasibility predicate respectively. Lowering the temperature by a specific rate, run for the desired number of iterations for generating all set of feasible assembly sequences. The detailed flow chart of simluated annealing technique is as follows in Fig. 2.

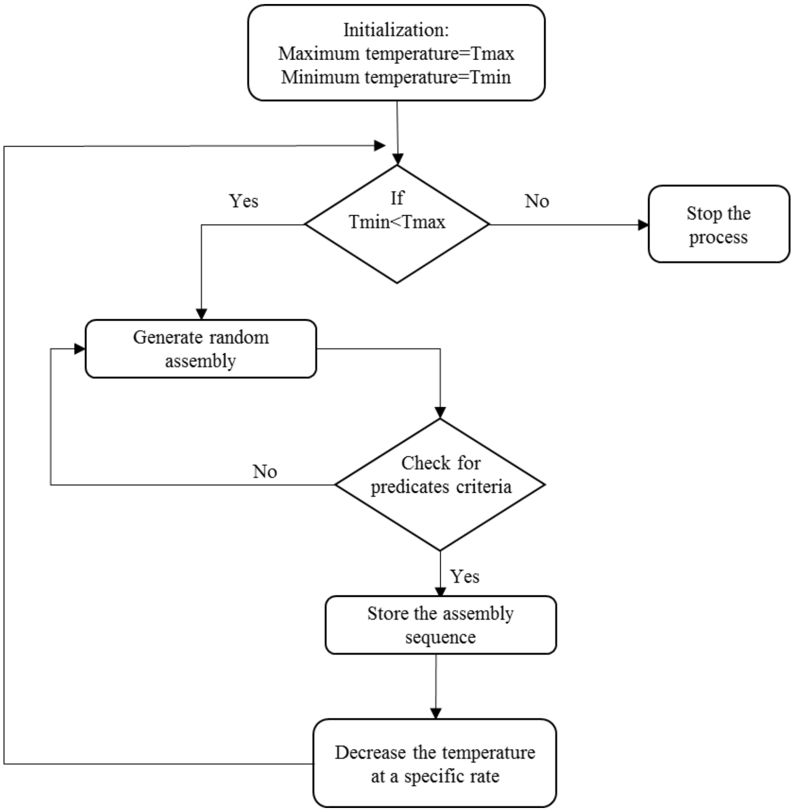

Fig. 2. Detailed flow chart of the SA for all set of feasible assembly sequences.

The temperature is decreased at a specific rate by the equation

$$t = e^{x} \tag{1}$$

$$x = (fp - fq)/T_{max} \tag{2}$$

Where fp is the fitness function of P
fq is the fitness function of Q

T_{max} is maximum temperature

4. DFA Methodology to reduce the levels in the assembly sequence

DFA methodology is applied to reduce the levels in the assembly sequences by considering the directional changes as objective function. In this methodology three criteria functionality, liaison predicate and material of the part have been used to test the assembly sequence for achieving the low levels of the assembly sequence. As the levels of the assembly sequence is reduced, cost of the assembly is reduced.

In the assembly sequence, to merge two parts as a single component initially they should have contact and same direction of sequence. After satisfying these two criteria, the two set parts have to check for the material and functionality. During merging of parts, the functionality of the parts should not disturb and should made of same material. The detailed methodology is explained using flow chart in Fig 3 is as follows.

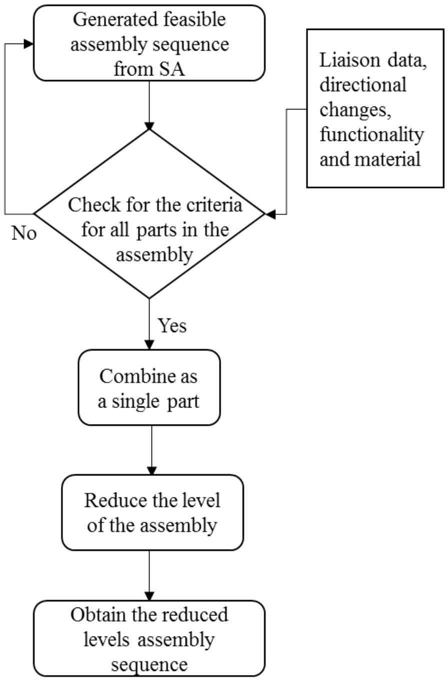

Fig. 3. Detailed flow chart of the DFA methodology

5. Results & Discussions

The developed methodology has been implemented on a hypothetical gear assembly for obtaining an optimum feasible assembly sequences. This assembly consists of nine parts (parts labelled with 1 to 9) as shown in Fig. 1and the possible sequences are 9-factorial. From the possible assembly sequences, SA technique generates 352 number of feasible assembly sequences. In the present work, a set of ten assembly sequences are considered for DFA concept to reduce the number of levels for the assembly sequence.

Assumptions:

1. Part 2& 3 are made of same material
2. Part 2 doesn't move relative to the part 3

Generally, the nine-part assembly consist of $n-1$ levels (i.e. 8 levels). The set of ten assembly sequences are considered as follows in table 2.

Table 2. A set of ten feasible assembly sequences from the 352 number of feasible assembly sequences.

S.No	Assembly Sequence	Direction	Direction changes
1	1-2-3-4-5-6-7-9-8	4-4-4-4-4-3-4-3-4	4
2	1-2-3-4-6-5-7-9-8	4-4-4-4-3-4-4-3-4	4
3	1-2-3-4-6-5-9-7-8	4-4-4-4-3-4-3-4-4	4
4	1-2-3-4-5-6-7-8-9	4-4-4-4-4-3-4-4-3	3
5	1-2-3-4-5-7-6-8-9	4-4-4-4-3-4-4-4-3	3
6	1-2-3-4-6-5-7-8-9	4-4-4-4-4-3-4-3-4	3
7	1-2-3-4-5-6-9-7-8	4-4-4-4-4-3-3-4-4	2

8	1-2-3-4-5-7-6-9-8	4-4-4-4-4-4-3-3-4	2
9	1-2-3-6-4-5-7-8-9	3-3-3-3-4-4-4-4-3	2
10	1-2-3-4-5-7-8-6-9	4-4-4-4-4-4-4-3-3	1

In this paper, analysis has been performed for two cases of industrial settings. A set of ten assembly sequences are considered for DFA analysis.

Case-1: Grouping the parts in the ten set assembly by considering the liaison predicate and directional changes.

Table 3. Optimum feasible assembly sequences for the considered ten sequences

S.No	Assembly Sequence	Direction	levels
1	1-(2-3)-(4-5)-6-7-9-8	4-(4-4)-(4-4)-3-4-3-4	6
2	1-(2-3)-(4-5)-6-7-8-9	4-(4-4)-(4-4)-3-4-4-3	6
3	1-(2-3)-(4-5)-7-6-8-9	4-(4-4)-(4-4)-3-4-3-4	6
4	1-(2-3)-(4-5)-6-9-7-8	4-(4-4)-(4-4)-3-3-4-4	6
5	1-(2-3)-(4-5)-7-6-9-8	4-(4-4)-(4-4)-4-3-3-4	6
6	1-(2-3)-6-(4-5)-7-8-9	3-(3-3)-3-(4-4)-4-4-3	6
7	1-(2-3)-(4-5)-7-8-6-9	4-(4-4)-(4-4)-4-4-3-3	6

In the above table 3. (2,3) and (4,5) represents one set of parts and (4-4) represents one set of directional changes. The optimum levels obtained for the assembly sequences are six.

Case-2: Checking the functionality and material of the grouped parts along with liaison predicate and directional changes.

Table 4. Optimum feasible assembly sequences

S.No	Assembly Sequence	Direction	levels
1	1-(2-3)-4-5-6-7-9-8	4-(4-4)-4-4-3-4-3-4	7
2	1-(2-3)-4-6-5-7-9-8	4-(4-4)-4-3-4-4-3-4	7
3	1-(2-3)-4-6-5-9-7-8	4-(4-4)-4-3-4-3-4-4	7
4	1-(2-3)-4-5-6-7-8-9	4-(4-4)-4-4-3-4-4-3	7
5	1-(2-3)-4-5-7-6-8-9	4-(4-4)-4-3-4-4-4-3	7
6	1-(2-3)-4-6-5-7-8-9	4-(4-4)-4-4-3-4-3-4	7
7	1-(2-3)-4-5-6-9-7-8	4-(4-4)-4-4-3-3-4-4	7
8	1-(2-3)-4-5-7-6-9-8	4-(4-4)-4-4-4-3-3-4	7
9	1-(2-3)-6-4-5-7-8-9	3-(3-3)-3-4-4-4-4-3	7
10	1-(2-3)-4-5-7-8-6-9	4-(4-4)-4-4-4-4-3-3	7

In the above table 4. (2,3) represents one set of parts and (4-4) represents one set of directions. The optimum levels obtained for the assembly sequences by considering functionality and material of the grouped parts along with liaison predicate and directional changes are seven.

6. Conclusion

Simulated annealing algorithm with CAD assistant along with DFA concept has been introduced in this research work to obtain optimal feasible assembly sequence for a given product. The developed methodology has been explained by considering a hypothetical gear assembly. In this two cases have been considered for reducing the number of levels of the assembly sequence. In case-1: liaison predicate and directional changes have been considered for grouping the parts as single set, which reduce the 9 levels assembly sequence to 6 levels assembly sequence. In case-2: the grouped parts have to check the functionality and material, which obtains the final assembly sequence of levels 7. The methodology is found to be successful in obtaining the optimal feasible assembly sequences by considering the functionality, material properties, liaison predicate and geometrical feasibility. As a future work, the developed algorithm can be applied effectively for larger assemblies.

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