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Assembly Sequence Planning for Products with Enclosed Shell

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Abstract

Aiming at the special structure of products with enclosed shell, the limitations of the usual methods are analyzed and concepts of axial subassembly and radial subassembly are proposed, the subassemblies are identified base on the adjacent matrix and interference matrix. A new kind of assembly relation matrix with the subassembly information is proposed to express the assembly model, the assembly transition probability in the ant colony algorithm is modified based on the assembly relation matrix and assembly precedence relations. The assembly sequence of products with enclosed shell can be planned rapidly with the algorithm aforementioned. Finally, the effectiveness was verified by an example.

***Keywords**: enclosed shell, axial subassembly, radial subassembly, assembly relation matrix, ant colony algorithm*

1. Introduction

The enclosed shell is an integral structure indivisible. The parts in the shell are assembled through several assembly holes and the assembly direction of some parts is a combination of several directions. The assembly process of products with enclosed shell depends on the experience and skills of professionals. Hence, the development cycle of new products is long and it is difficult for enterprises to react to the market in time. The assembly cost can be reduced and the development cycle can be decreased by assembly sequence planning based on computer technology. So the method has important significance.

Plenty of research works about assembly sequence planning have been carried out. (1) The algorithm based on assembly precedence relations, assembly process knowledge was introduced into the algorithm, a feasible assembly sequence was obtained with this algorithm based on human-computer interaction [1-3]. (2) Assembly sequence planning was transformed into disassembly of products, the inverse process of disassembly sequence was used as the assembly sequence [4]. Aiming at the combination explosion in assembly sequence planning for products with plenty of parts, the concept and identification method of subassembly were introduced into the method [5-7]. Intelligent algorithms were applied to assembly sequence planning, mainly the genetic algorithm, artificial neural network algorithm, ant colony algorithm and immune algorithm, new methodologies were designed by combined use of these intelligent algorithms [8-13]. The aforementioned intelligent algorithms were improved in some new algorithms, the improved ones had advantages in global optimal search ability and convergence rate [14-16].

The common methods are not fully applicable to products with enclosed shell, hence, the concepts and identification methods of axial subassembly and radial subassembly are proposed in this paper, a new kind of assembly relation matrix with subassembly information is built to express the assembly model. Combined with assembly relation matrix and assembly precedence relations, the assembly transition probability in the ant colony algorithm is modified, the assembly sequence of products with enclosed shell can be planned rapidly with the algorithm. The flow chart of the algorithm is shown in Figure 1.

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2. Identification of Subassembly for Products with Enclosed Shell

Assembly sequence planning for products with enclosed shell is a combinatorial optimization problem with strong constraints. For the purpose of reducing the complex degree and obtaining the optimal sequence with the ant colony algorithm, the subassemblies are identified firstly so that the algorithm for products with enclosed shell could be more specific and the assembly sequence could be planned rapidly.

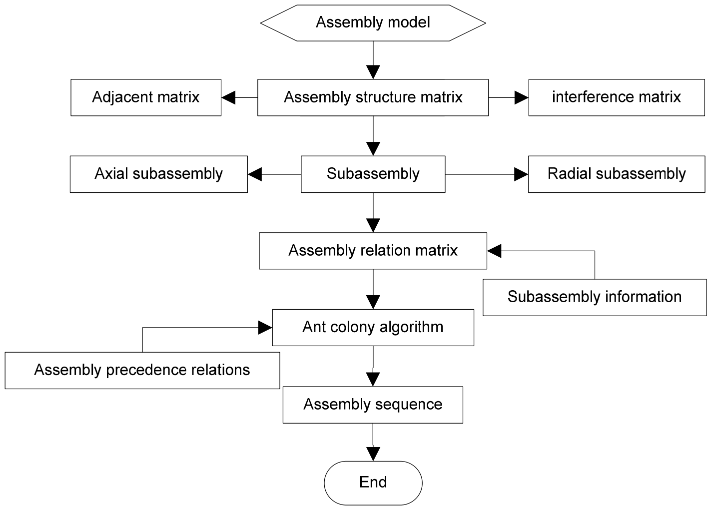


Figure 1. Flow Chart of Algorithm

The assembly of common products can be expressed by graph theory, the subassemblies are identified based on the assembly construct information expressed by the adjacent matrix *C* and the interference matrix *A*, but the diversity and complexity could cause invalidation. The product as shown in Figure 2 is a typical example of products with enclosed shell, the assembly and disassembly of some components could not be completed in a single direction. For example, before the gear being installed to the appointed position along the shell, it should be installed into the shell through the location of the end cover.

Aiming at this problem, the following concepts are proposed:

Concept1. Axial subassembly, represented by S_a: Subassemblies which can be assembled and disassembled along the axial direction of shaft parts directly.

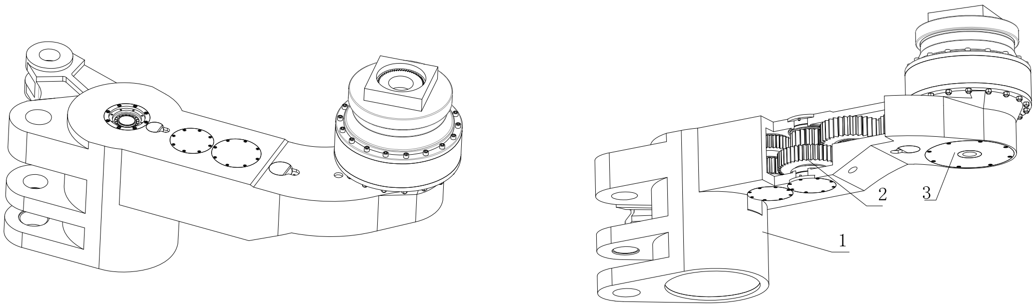
Concept2. Radial subassembly, represented by S_r: Subassemblies which must be moved along the radial direction of shaft parts during the assembly and disassembly process along the axial direction.

During the identification process of subassembly identification for products with enclosed shell, S_a is in preference of S_r. During the identification process of S_r, the foundation part is not considered. The process of the subassembly identification for products with enclosed shell is as follows.

1) Select the foundation part.

2) Obtain the adjacent matrix and interference matrix based on the assembly relations.

3) Let *b* be the foundation part, p_i is an alternative part of the axial subassembly and S_{ap} is the set of all the alternative parts of the axial subassembly. S_{rp} is the set of all the alternative parts of the radial subassembly which is composed of all the parts except for the alternative parts of the axial subassembly and except for the foundation part.



1-Shell, 2-Gear, 3-End cover

Figure 2. A Typical Product with Enclosed Shell

4) Identify the axial subassemblies with the usual method [6].

5) Identify the radial subassemblies without considering the foundation part.

Practice has shown the existence of feasible sequences in which subassemblies are assembled dividedly, hence, the subassembly information is considered as priority condition but not forcible condition.

3. Assembly Relation Matrix of Products with Enclosed Shell

The assembly sequence is expressed by an ordered set of assembly operations, the set is determined by the assembly relations between parts of the product, hence, the assembly sequence planning is regarded as operations and calculations of the assembly relations. The relevant information of assembly relations is expressed by assembly relation matrix from which the type of subassemblies, assembly direction and component code can be obtained: the type of subassembly is S_a or S_r, it is identified by the algorithm introduced in previous part of the paper; the assembly direction of S_a is ±*Y* and that of S_r is a combination of ±*Y* and ±*X*, the component code is arranged according to the distance with the assembly hole, the longer is the distance between the part and the assembly hole, the bigger is the node.

3.1. Assembly Relation Matrix

The assembly relation matrix is a matrix for the assembly relationships between parts. The assembly relation matrix of an assembly composed of *n* parts $p_1, p_2, ..., p_n$ is shown as (1), where $r_{ij} = a_{ij} I_{ij} n_{ij}$, a_{ij} is the interference condition between p_i and p_j, when p_i is disassembled along +*Y*, $a_{ij} = 1$ if interference with p_j occurs, otherwise $a_{ij} = 0$, I_{ij} is the relationship of subassembly style between p_j and p_i, the value of I_{ij} is shown in Table 1, n_{ij} is the relationship of component code between p_j and p_i, if the component code of p_i is smaller than that of p_j, n_{ij}=-1, if bigger, n_{ij}=1, if the two codes are equal, n_{ij}=0.

$$R = \begin{array}{c} \\ P_1 \\ P_2 \\ \cdots \\ P_n \end{array} \begin{array}{c} \begin{array}{cccc} P_1 & P_2 & \cdots & P_n \end{array} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \end{array} \quad (1)$$

Every component factor of r_{ij} includes several values. For the purpose of reducing the complex degree of the sequence planning, assembly precedence relations of the product are introduced into the algorithm. The assembly precedence relation is the relation of all the parts according to the assembly order, it is the internal constraint relation during the assembly process. The assembly work cannot be completed successfully without the assembly precedence relations. For example, the radial subassembly should be assembled before the axial subassembly which has assembly relation with it. There are different priority level corresponding to different values of r_{ij}.

Table 1. Value of I_{ij}

$P_i \backslash P_j$	S_a	S_r
S_a	-2	-1
S_r	1	2

3.2. Feasible Assembly Direction

The assembly direction of S_a is ±*Y* and that of S_r is a combination of ±*Y* and ±*X*. The feasible assembly direction of each part is derived from assembly relation matrix.

Let *E* be a part to be assembled and it belongs to S_a, let S_c be a temporary assembly composed of parts assembled, $S_c = \left(p_1, p_2, ..., p_m\right)$. In order to describe the feasible assembly direction, variable $U = \{+a_y, -a_y\}$ was put forward, the two elements represent the assembling ability in +*Y* direction and –*Y* direction. If the part can be assembled without interference in a direction, the value of corresponding variable is 0, otherwise, the value is 1. The calculation method of $+a_y$ and $-a_y$ is shown as (2).

$$\begin{aligned} +a_y &= a_{P_1E} + a_{P_2E} + \ldots + a_{P_mE} \\ -a_y &= a_{EP_1} + a_{EP_2} + \ldots + a_{EP_m} \end{aligned} \tag{2}$$

If p_i and *E* belong to the same subassembly, $a_{P_1E} = a_{EP_1} = 0$, otherwise, the value should be extracted from the assembly relation matrix.

The assembly direction of the part to be assembled can be calculated by (2): the part could not be assembled if $+a_y > 0$ and $-a_y > 0$, the sequence including the assembly operation afore mentioned is not feasible and should be modified; the assembly direction is –*Y* if $-a_y > 0$; the assembly direction is +*Y* if $+a_y > 0$.

If the part belongs to S_r, the assembly direction is represented by $\pm YR_a$ which means a combination of ±*Y* and ±*X*. The assembly direction along the *Y* axis will affect the position and posture of the foundation part and it can be calculated by (2).

Let *E* be a part to be assembled and it belongs to S_r, let S_c be a temporary assembly composed of all the radial subassemblies assembled. If $-a_y > 0$, the sequence including the assembly operation afore mentioned is not feasible and should be modified.

Let S_c be a temporary assembly composed of all the radial subassemblies with a smaller component code than *E*. if $+a_y > -a_y$, the assembly direction is a combination of +*Y* and ±*X* and it is represented by $+YR_a$; if $-a_y > +a_y$, the assembly direction is a combination of -*Y* and ±*X* and it is represented by $-YR_a$; if $-a_y = +a_y$, the part can be assembled in the two directions above and the assembly direction is represented by $\pm YR_a$.

During the assembly process, if the assembly direction of the part is changed between $+YR_a$ or +*Y* and $-YR_a$ or -*Y* , the position and posture of the foundation part will be changed so that the product can be assembled properly.

4. Assembly Sequence Planning Based on ACA

The ant colony algorithm is a kind of simulated evolutionary algorithm proposed by Marco Dorigo in 1991. The natural ants are able to find the shortest path between the hideout and the foods. When the ant encounters a new crossroad, the next path is selected stochastically, meanwhile, pheromone related to path length is secreted, the shorter is the path the more is the amount of the pheromone and the path will be selected with more possibilities. The pheromone on all of the paths will volatile gradually. The shortest path will be found based on the pheromone. The ant colony algorithm has advantages in combinatorial optimization problems, and the algorithm has been applied to related fields [17-19].

4.1. Assembly Transition Probability

Assembly transition probability is the selection probability of the next part in an assembly sequence. To ant *k*, the corresponding part with bigger probability is more likely to be selected. Assuming that the ant will not select the part selected, tabu list is a set of parts selected by ant *k*, expressed as *tabuk*(*k*=1,2,…,*n*). At the moment *t*, the assembly transition probability to node *j* from node *i* $P_{ij}^{k}(t)$ is shown as (3) where τ_{ij} is the concentration of pheromone, rc_{ij} is the relation guidance factor, d_{ij} is the assembly guidance factor.

$$P_{ij}^{k}(t)=\begin{cases}\dfrac{[\tau_{ij}(t)]^{\alpha}[rc_{ij}(t)]^{\beta}[d_{ij}(t)]^{\mu}}{\sum_{k\in allow_k}[\tau_{ij}(t)]^{\alpha}[c_{ij}(t)]^{\beta}[d_{ij}(t)]^{\mu}}, & j\in allow_k\\ 0, & \text{Otherwise}\end{cases} \tag{3}$$

The value of rc_{ij} is shown as (4). If all of the residual parts can be assembled, d_{ij}(t)=1, otherwise, d_{ij}(t)=0. α, β and μ is respectively the weight coefficient of τ_{ij}, c_{ij} and d_{ij}. $allow_k$ is the set of optional parts in the current state.

$$rc_{ij}(t)=\begin{cases}1.0, & I_{ij}n_{ij}=(2,0)、(2,1)\\ 0.8, & I_{ij}n_{ij}=(1,0)、(1,1)、(2,-1)\\ 0.6, & I_{ij}n_{ij}=(-2,0)\\ 0.4, & I_{ij}n_{ij}=(-2,1)、(-1,-1)\\ 0.2, & I_{ij}n_{ij}=(-2,-1)\\ 0, & I_{ij}n_{ij}=(-1,0)、(-1,1)、(1,-1)\end{cases} \tag{4}$$

4.2. Update Rule of Pheromone

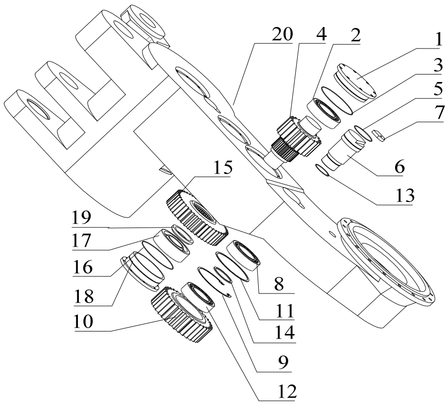
The pheromone secreted by ants will influence the selection behavior of the following ants. During the process of optimization, the pheromone on the path should be updated according to the local update rule and the global update rule [15]. During the update process, the evaluation function of the assembly sequence is an important influence factor. The evaluation function of the assembly sequence is measured by the assembly redirection times and concentration of the sequence and the evaluation function is shown as (5) where *D* is the times of assembly redirection, *G* is the times of separation of a subassembly during the assembly process, ω_1, ω_2 is respectively the weight coefficient of *D* and *G*.

$$S=\omega_1\times D+\omega_2\times G+1 \tag{5}$$

5. Example Verification

A typical product with enclosed shell as shown in Figure 2 is taken as an example to verify the algorithm in this paper. The exploded view of the product is shown in Figure 3, there are 20 parts without considering the bolts and other connectors.

In order to verify the algorithm, a Visual Basic program is compiled. The identification result of subassemblies is as follows: foundation part 20, axial subassembly S_{a1}(1, 3), S_{a2}(2, 4), S_{a3}(16, 18), S_{a4}(5, 6, 13), S_{a6}(17), S_{a7}(19), S_{a8}(7), radial subassembly S_{r1}(8, 9, 10, 11, 12, 14), S_{r2}(15).



1-Upper end cover, 2-Bearing NJ2218E,3-O ring seal 175×3.55-1, 4-Gear shaft,5- O ring seal 109×3.55,6-Idler shaft, 7-Pressure plate, 8-Bearing 22220CC/W33-1,9-Inner ring rib, 10-Idle gear, 11-Distance sleeve-1, 12-Bearing 22220CC/W33-2,13- O ring seal 69×2.65, 14- Distance sleeve-2, 15-Gear, 16- O ring seal 175×3.55-2,17-Bearing NJ2215E,18- Lower end cover,19- Distance sleeve-3, 20-Shell

Figure 3. Partial Structure of Rocker Arm

The assembly relation matrix shown in Figure 4 is obtained based on the subassembly information and the interference matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0-2 0	1-2 0	1-2 0	1-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	1-1 0	1-2 0	1-2 0	1-2 0	1-2 0	1-1 0
2	0-2 0	0-2 0	0-2 0	1-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	1-1 0	0-2 0	1-2 0	1-2 0	1-2 0	0-1 0
3	1-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	1-1 0	1-2 0	0-2 0	1-2 0	0-2 0	0-1 0
4	0-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	1-1 0	0-2 0	1-2 0	1-2 0	1-2 0	0-1 0
5	0-2 1	0-2 1	0-2 1	0-2 1	0-2 0	1-2 0	0-1 0	1-1 0	0-1 0	0-1 0	0-1 0	1-1 0	0-2 0	1-1 0	0-1 1	0-2 1	0-2 1	0-2 1	0-2 1	1-1 1
6	0-2 1	0-2 1	0-2 1	0-2 1	1-2 0	0-2 0	0-1 0	1-1 0	0-1 0	0-1 0	0-1 0	1-1 0	1-2 0	1-1 0	0-1 1	0-2 1	0-2 1	0-2 1	0-2 1	1-1 1
7	0 1 1	0 1 1	0 1 1	0 1 1	1 1 0	1 1 0	0 2 0	1 2 0	1 2 0	1 2 0	1 2 0	1 2 0	0 1 0	1 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
8	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	1 2 0	0 2 0	1 2 0	1 2 0	0 1 0	1 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
9	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	0 2 0	1 2 0	1 2 0	1 2 0	0 1 0	0 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
10	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	1 2 0	0 2 0	0 2 0	0 2 0	0 1 0	0 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
11	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	0 2 0	0 2 0	0 2 0	1 2 0	0 1 0	0 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
12	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	0 2 0	0 2 0	0 2 0	0 2 0	0 1 0	0 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
13	0-2 1	0-2 1	0-2 1	0-2 1	0-2 0	1-2 0	0-1 0	0-1 0	0-1 0	0-1 0	0-1 0	0-1 0	0-2 0	0-1 0	0-1 1	0-2 1	0-2 1	0-2 1	0-2 1	1-1 1
14	0 1 1	0 1 1	0 1 1	0 1 1	0 1 0	0 1 0	0 2 0	0 2 0	0 2 0	0 2 0	0 2 0	1 2 0	0 1 0	0 2 0	0 2 1	0 1 1	0 1 1	0 1 1	0 1 1	1 2 1
15	0 1 0	0 1 0	0 1 0	0 1 0	0 1-1	0 1-1	0 2-1	0 2-1	0 2-1	0 2-1	0 2-1	0 2-1	0 1-1	0 2-1	0 2 0	1 1 0	1 1 0	1 1 0	1 1 0	1 2 0
16	0-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	0-1 0	0-2 0	0-2 0	1-2 0	0-2 0	0-1 0
17	0-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	0-1 0	0-2 0	0-2 0	1-2 0	0-2 0	0-1 0
18	0-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	0-1 0	1-2 0	0-2 0	0-2 0	0-2 0	0-1 0
19	0-2 0	0-2 0	0-2 0	0-2 0	0-2-1	0-2-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-1-1	0-2-1	0-1-1	0-1 0	0-2 0	1-2 0	1-2 0	0-2 0	0-1 0
20	0 1 0	0 1 0	0 1 0	0 1 0	0 1-1	0 1-1	0 2-1	1 2-1	1 2-1	1 2-1	1 2-1	1 2-1	0 1-1	0 2-1	1 2 0	0 1 0	0 1 0	1 1 0	0 1 0	0 2 0

Figure 4. Assembly Relation Matrix

According to experience, the number of ants should be the same to that of the parts in the assembly approximately, as the subassembly information and the assembly precedence relations are introduced into the algorithm, the number of ants can be reduced to some extent.

The number of ants is 10 in this paper, other parameters are shown in Figure 6, the result of 100 iterations is shown in Figure 5, during the iterative procedure, with the accumulation of the experience, the sequence with the lowest composite cost was found by the ant colony.

The algorithm is implemented through Visual Basic Programing. The best sequence is shown in Table 2. The result includes the assembly sequence and the assembly directions of all the parts. The planning result interface is shown in Figure 6. The times of assembly redirection is 1 and the times of separation of a subassembly is 0 during the assembly process, the composite cost is 0.8. A series of unworkable sequences and sequences with high composite cost are abandoned by the algorithm. The product can be assembled according to the final sequence with a low composite cost and the effectiveness of the algorithm is verified.

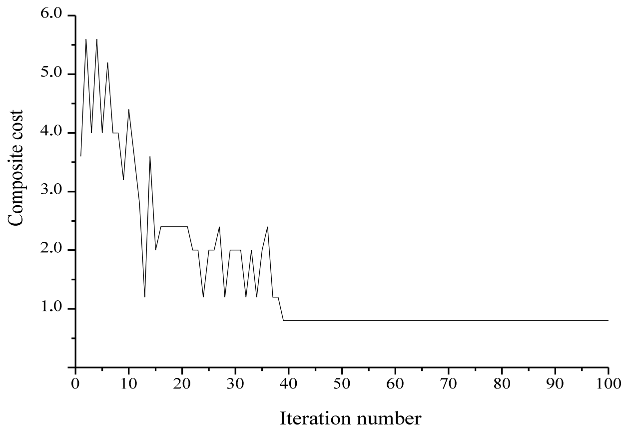


Figure 5. Convergence Curve of Ant Colony Algorithm

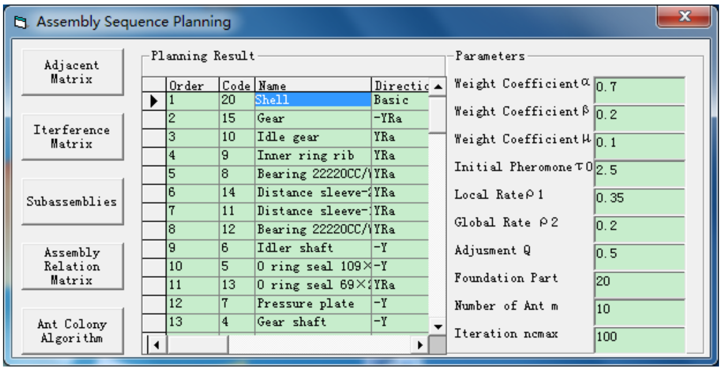


Figure 6. Planning Result Interface

Table 2. Planning Result

Order	Code	Name	Direction
1	20	Shell	Basic
2	15	Gear	$-YR_a$
3	10	Idle gear	YR_a
4	9	Inner ring rib	YR_a
5	8	Bearing 22220CC/W33-1	YR_a
6	14	Distance sleeve-2	YR_a
7	11	Distance sleeve-1	YR_a
8	12	Bearing 22220CC/W33-2	YR_a
9	6	Idler shaft	$-Y$
10	5	O ring seal 109×3.55	$-Y$
11	13	O ring seal 69×2.65	$-Y$
12	7	Pressure plate	$-Y$
13	4	Gear shaft	$-Y$
14	2	Bearing NJ2218E	$-Y$
15	1	Upper end cover	$-Y$
16	3	O ring seal 175×3.55-1	$-Y$
17	19	Distance sleeve-3	$+Y$
18	17	Bearing NJ2215E	$+Y$
19	16	O ring seal 175×3.55-2	$+Y$
20	18	Lower end cover	$+Y$

6. Conclusion

A new assembly sequence planning method suitable for products with enclosed shell is proposed based on further study on the existing methods and the assembly process of products with enclosed shell. The rocker arm of shearer is taken as an example to prove the practicability of the algorithm. The following conclusions are drawn:

(1) Because of the special structure of products with enclosed shell, the axial subassembly and radial subassembly are identified separately, and the axial subassembly is in preference of radial subassembly during the identification process.
(2) The assembly sequence planning is regarded as an operation and calculation of the assembly relationships. The complex degree of the sequence planning for products with enclosed shell can be reduced with the assembly relation matrix including the subassembly information.
(3) The assembly transition probability in ant colony algorithm was modified based on the assembly relation matrix and the assembly precedence relation, the algorithm is suitable for products with enclosed shell.

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