

A general approach to optimize disassembly sequence planning based on disassembly network: A case study from automotive industry

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ABSTRACT

Disassembly sequences is a key element of products recycling or remanufacturing, and related with the recycling quality or maintenance cost. In order to improve the performance of the disassembly operation, this paper analyzes the disassembly information on automobile parts and draws the disassembly network graph by using evolution rules of the AND/OR graph. Then a disassembly model of automobile parts is established. Considering the mapping between the Floyd-Warshall algorithm and the automobile disassembly mode, we obtain the optimal disassembly sequence by solving the weighted disassembly model. Finally, a case study on automotive silicone oil fan clutch is given to illustrate the procedure. This approach could be used to obtain optimum disassembly routes of products containing complex AND/OR hierarchical relationships.

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ARTICLE INFO

Keywords:

Automotive industry
Automotive parts
Disassembly sequence
Disassembly model
Disassembly network
Floyd-Warshall algorithm

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Article history:

Received 17 January 2017
Revised 21 July 2017
Accepted 19 September 2017

1. Introduction

Manufacturing industry has become a leading industry during the economy development, while manufacturing industry produces large amounts of waste, which causes heavy environment pollution [1]. In addition, improper use of industrial waste products (e.g. burying) aggravates the environment. The production of vehicles, as a mass consumer good, increases year by year, so does the number of scrapped cars. In one car, more than 70 % of the parts are made of metal, which belongs to renewable resources. If no appropriate action is taken for resource re-use, there will be a huge waste for the society. China and the European Union have introduced relevant laws and regulations which stipulate that the car manufacturers must recycle its own branded products. As the first step of automobiles recycling, how to determine the effective disassembly sequence has become one of the hot spots in the field of automobiles recycling.

The automobile disassembly sequence planning problem studies how to determine the optimal sequence based on assembly relations between different parts and techniques of process. A good disassembly sequence can reduce the time and cost of disassembly, which also improves the efficiency of disassembly and the recycling rate of waste products. For a long time, due to the

low level of technology for disassembly and recycling, the disassembly of automobile products are still mainly manual disassembly, which depends on the demolition skills of workers. Workers could find optimal disassembly sequence with their own experience when the size of disassembly is small. However, under the situation of the large disassembly size, finding an efficient disassembly sequence will become more difficult by only human experience. Thus finding an effective method for the disassembly sequence of the automobile product to make a reasonable planning will improve the efficiency of disassembly and the reuse rate of the product.

Two main steps are comprised in specifying the best disassembly sequence: (1) generating a set of feasible disassembly sequences, and (2) finding the most efficient sequence among these feasible solutions [2, 3]. Lambert conducted a brief survey on disassembly sequence planning problem [4]. In their paper, many solution methods have been introduced, including empirical methods, graphical methods, fuzzy method, e.g. simulated annealing [5], search algorithms and mathematical programming, e.g. linear programming [6], mixed integer programming.

The graph-based models, used to represent various disassembly sequences, includes undirected graphs, digraphs, AND/OR graphs, Petri nets, and so on [7-14]. In addition, most of researchers have concentrated on the second step that is to find the best disassembly sequence. Moore *et al.* discuss a Petri net-based method to generate disassembly process plans automatically for product with AND/OR disassembly precedence relationships [7]. De Mello and Sander-so solve the assembly problem using AND/OR graph theory [8]. But at the same time the disassembly operation is regarded as the inverse process of assembly. Zhang and Kuo and Zhang *et al.* use undirected graph theory to generate the model, while the depth and breadth is used for search algorithm to optimize the product disassembly sequence [9, 10]. Tiwari *et al.* use Petri net and cost evaluation parameters to study the disassembly sequence planning problem [11]. Zussman and Zhou use Petri net theory for product disassembly modelling, then apply adaptive algorithm to solve the model, and finally achieve the planning and optimization of product disassembly sequence [12]; Tang *et al.* further consider the disassembly uncertainty characteristic on the basis of the Petri net, and analyse the average time of the disassembly process [13].

Many heuristic algorithms have been applied in solving disassembly sequence planning problem, and achieved certain results. Li *et al.*, Kongar and Gupta set the remove time shortest and the times of disassembly direction changes least as the goal, and research the optimal disassembly sequence using the genetic algorithm [5, 15]. Adenso-Díaz *et al.* set the disassembly cost as the evaluation index, using a greedy randomized adaptive search algorithm to research the optimal disassembly sequence. At the same time, the paper also combines the path connection method in heuristic algorithms and the greedy random adaptive search algorithm, which obtains the optimization of the disassembly sequence with the double sides [16]. Failli and McGovern and Gupta Dini apply the ant colony algorithm to the disassembly sequence planning problems, and the disassembly sequence is optimized [17, 18]. Lye *et al.* establish a hierarchical product network that comprise different costs incurred during disassembly, and the multiple service action (MSA) algorithm then determines the minimum servicing cost based on Floyd's algorithm, a shortest path algorithm [19]. In addition, González and Adenso-Díaz apply the distributed search algorithm to the product disassembly sequence planning with a sequence dependent cost [20].

The purposes of disassembly are different. Some are for the maintenance or upgrade of the target component, and some are for recycling end-of-life products. As a result, there are three types of disassembly: complete, incomplete, and selective disassembly. Complete disassembly is a process that all subassemblies in a product are separated from each other, which is usually uneconomic. The incomplete disassembly, in which only part units are disassembled, aims to determine the appropriate disassembly level. According to Kang and Xirouchakis, most disassembly planning research has been concentrated on end-of-life products, which is incomplete disassembly planning. In the disassembly planning problem, part of the literatures works on the incomplete disassembly planning of abandoned products [21]. Behdad *et al.* study the incomplete disassembly planning, which applies mathematical model to obtain the optimal sequence of disassembly [22]. The purpose is to recycle the value of waste products. In contrast to incomplete disassembly, selective disassembly is for the purpose of maintenance or upgrade. It disassembles a determined component, which means that the target component is known. Srinivasan

and Gadh and Srinivasan *et al.* use wave propagation method to analyse and optimize the selective disassembly sequence [23, 24]. Since the set of products or components which needs to be disassembled has a topological structure, the selective disassembly sequence planning can be studied by using the wave level relation. Kara *et al.* propose a model for the selective disassembly sequence of the parts with a certain value for reusing, which can be used to reduce the disassembly time [25]. Chung and Peng point out that the wave propagation method can solve the selective disassembly sequence, but it can only solve products with a topological structure, ignoring the possibility of batch disassembly [26].

In this paper, based on the information of automobile parts, a reasonable product disassembly model is proposed using the network graph, which is used to express the relationship between the units [27-30]. This paper will transform the optimal disassembly sequence problem into the shortest path problem, aiming at planning and solving complete disassembly sequences, target (selective) disassembly sequences and economic optimal disassembly sequences (incomplete disassembly planning) combining with the Floyd-Warshall algorithm. The results show the validity of the model and algorithm.

The remaining of the paper is as follows: Section 2 proposes the disassembly sequence planning model on the basis of AND/OR graph. Section 3 combines the Floyd-Warshall algorithm with the disassembly sequence planning problem. In section 4, we analyse the disassembly sequence planning problem of the automotive silicone oil fan clutch, and test the proposed approach on silicone oil fan clutch disassembly network. Section 5 summaries the research of this paper, and the future research direction is pointed out.

2. Problem formulation

In the disassembly planning problem of automobile parts, the sequence is composed of four parts: the extraction of disassembly information, the establishment of the disassembly model, the generation of disassembly sequence, the evaluation and optimization of disassembly sequence. At present, the method based on graph theory is one of the methods for the generation and optimization of disassembly sequence [14, 31]. In the disassembly information model of the automobile parts, the parts in the process of disassembly are represented by a node, and the side is used to represent a disassembly operation. Through the processing and calculation of the graph, the corresponding disassembly sequence scheme is obtained. AND/OR graph has special advantages. In this section, we will introduce the extraction of disassembly information and the establishment of the model, respectively.

2.1 Disassembly network model

Disassembly network based on the AND/OR graph

In this paper, a disassembly model based on AND/OR graph is established. The node in the network represents the state of the parts in the disassembly process, and the side represents the operation process. And the main ideas of AND/OR graph is as follows:

In Fig. 1, assuming that "A" is the original problem, this problem can be decomposed into three sub problems: "A1", "A2", and "A3". If "A1, A2, A3" three sub problems can all be solved, then the original problem "A" can be solved too, which means "and relationship" exists between the three sub problems "A1, A2, A3". Node "A" is called "and node". As shown in Fig. 1(a), the tree constituted by "A, A1, A2, and A3" is called as "and tree". In the graph, to represent "And nodes", we use an arc to connect each edge which connects the AND node and its sub nodes. If there exist one solution between "A1, A2, A3", the original problem "A" is solvable, which is called an "or relationship" between the three sub problems "A1, A2, A3". Node "A" is called "or node". As shown in Fig. 1(b), the tree constituted by "A, A1, A2 and A3" is called as "or tree". If the above two trees are combined, the graph is called AND/OR graph. AND/OR graph contains and nodes and or nodes, as shown in Fig. 1(c).

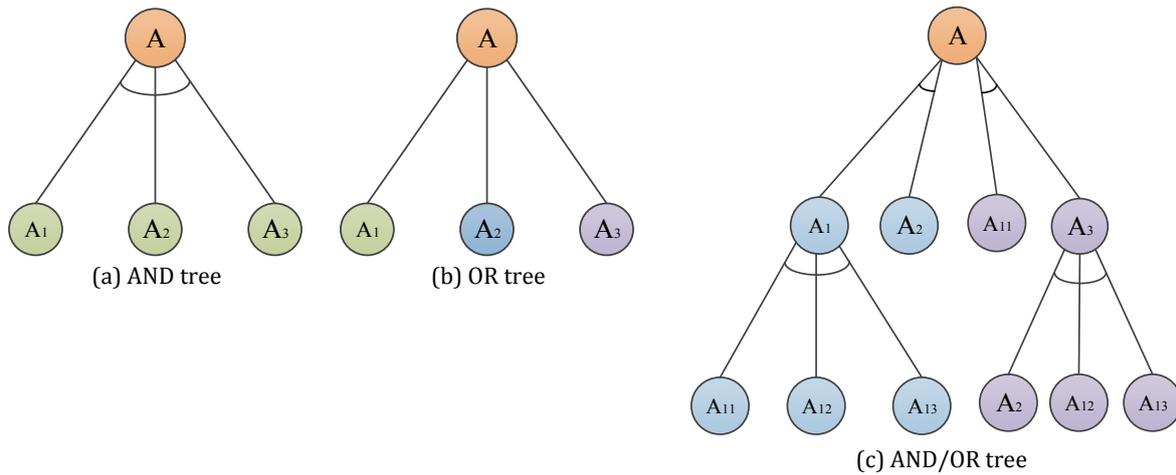


Fig.1 Graphical representation of the AND/OR tree

When using AND/OR graph to describe the disassembly sequence of the automobile product, node “A” represents the product, “A1, A2, A3, A11, A12 and A13” represent feasible subassemblies, and the edge indicates feasible disassembly operation. The process from the top node “A” to the bottom represents a product disassembly process. There are two ways for disassembling “A” product. In the first one we can disassemble “A” into “A1” and “A2”, then disassemble “A1” into “A11, A12 and A13”. In the other one “A” is first disassembled into “A3 and A11”, then “A3” is disassembled into “A2, A12 and A13”.

While the AND/OR graph cannot develop into the disassembly network directly. But we can design reasonable evolution rules to obtain the network diagram from the disassembly AND/OR graph. The corresponding evolution rules are defined as follows:

Rule 1: The establishment disassembly network is different from the top-down approach of AND/OR graph. It searches the entire possible disassembly paths from the bottom of the AND/OR graph to the top.

Rule 2: In a bottom-to-up search process, we store all the parts in the *and tree* at a node. If there is a relationship between all parts of an *and tree*, then find all possible disassembly ways. If there is no relationship between all parts of an *and tree*, set each part as an independent node. Connect all nodes with short lines without a specific order.

Rule 3: If there are more than one disassembly ways for a node in the graph. This node will be converted into different disassembly paths in the search progress.

In Rule 2, we connect the parts with short lines, but there is no disassembly relationship between parts. This paper simplifies the disassembly network graph based on the AND/OR graph. The simplified rules are as follows:

Rule 4: Delete all the individual parts of the transition graph, and reserve the part nodes, and connect them with short lines.

Rule 5: Define the node of part set. Connect the set of parts which can be disassembled into parts by one disassembly operation and the nodes of set of parts. The disassembly network will finally go into one node, representing the end of complete disassembly.

To illustrate the AND/OR graph and the model of disassembly graph, the analysis of the piston connecting rod unit (exclude piston part) in automobile is presented. Its assembly drawing is as shown in Fig. 2.

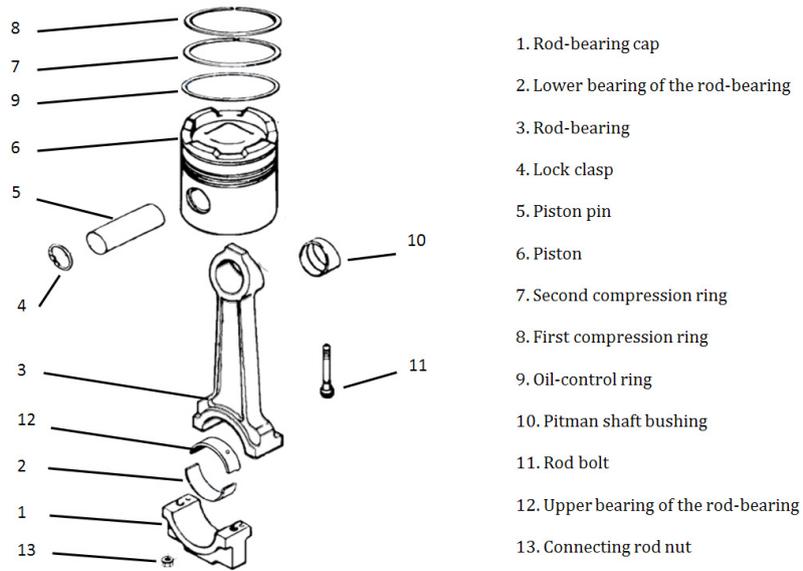


Fig. 2 Explosion diagram of piston connecting rod group

The AND/OR graph of rod-bearing part is shown in Fig. 3.

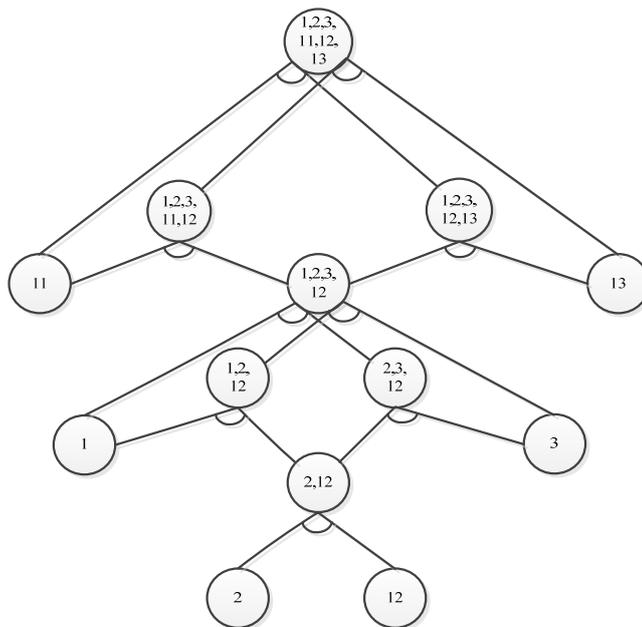


Fig. 3 The AND/OR graph model of the rod-bearing part

According to the rules described above, the AND/OR graph of the piston rod can be transformed into a graph, as shown in Fig. 4.

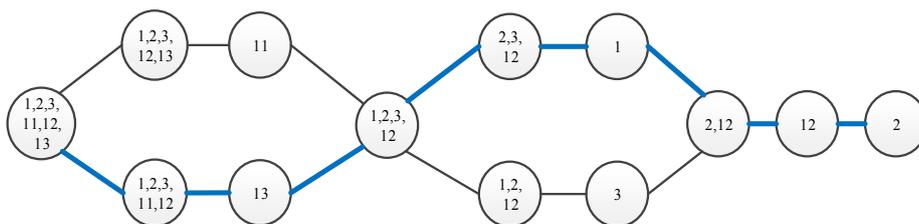


Fig. 4 The disassembly network graph of the rod-bearing part

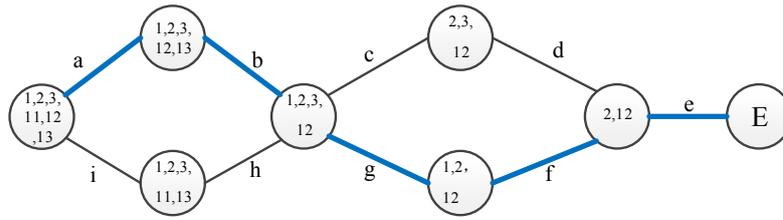


Fig. 5 Simplified graph of the disassembly network of the rod-bearing part

The disassembly network can be illustrated as Fig.4. The bold path represents a feasible disassembly sequence of piston group. According to Rules 4 and 5, the simplified graph is shown in Fig. 5.

The order of disassembly is from left to right in the simplified graph. The first point on the left side indicates the original product, that is, the starting point of the disassembly, while node “E” is the final disassembly state. The bold path is a disassembly sequence of piston connecting rod group. We take the piston connecting rod as an example to establish the transition matrix and the weighted adjacency matrix of the disassembly graph. In Fig. 6, numbers represent node and letters stand for disassembly steps.

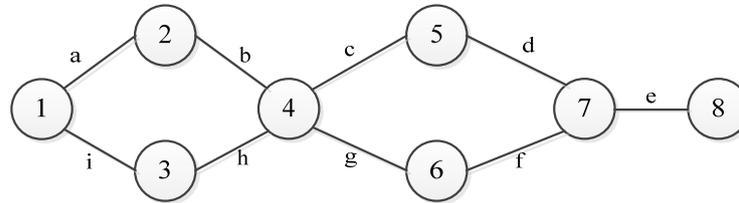


Fig. 6 The network graph of the rod-bearing part

Weight adjacency matrix of network

In order to formulate the disassembly process, this paper defines part set *S* and disassembly step set *A* to describe the states of parts and disassembly steps in the process of disassembly. Where *S* describes all possible parts that exist in the disassembly process (the original scrap product is also included in set *A*). Set *A* contains all the operation steps in the disassembly. Therefore, the simplified disassembly network can be represented by a *S* × *A* transition matrix *T*, and the elements in the matrix *T* are defined as follows:

$$a_{ij} \begin{cases} -1 & \text{Node } i \text{ is the starting point of } i \text{ to } j \\ 1 & \text{Node } i \text{ is the ending point of } i \text{ to } j \\ 0 & \text{Node } i \text{ is connected of } i \text{ to } j \end{cases} \quad (1)$$

Each row of the matrix corresponds to a part or a unit, and each column corresponds to an operation step. Matrix elements in the disassembly represent: if a disassembly step represents that a unit is disassembled, then the element is set as -1; if a disassembly step represents that the parts are assembled into a unit, then the element is set as 1, while the remaining elements in the matrix are 0.

This example illustrates the transition matrix of the network graph in Fig. 6 based on Eq. 1:

$$T = \begin{matrix} & \begin{matrix} a & b & c & d & e & f & g & h & i \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{matrix} & \begin{vmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{vmatrix} \end{matrix}$$

Weight adjacency matrix of the directed graph: If each side has a value in directed graph $D = (V, E)$, then D is called weighted directed graph. If D is a simple weighted directed graph, the weight adjacency matrix of D is $W = (a_{ij})_{n \times n}$. The elements of matrix W are defined as follows:

$$a_{ij} = \begin{cases} w_{ij} & \text{if } (v_i, v_j) \in E \text{ and } w_{ij} \text{ is its weight} \\ 0 & \text{if } i = j \\ \infty & \text{if } (v_i, v_j) \notin E \end{cases} \quad (2)$$

Disassembly network graph is a directed graph, and different disassembly purposes correspond to different weights. For example, if the goal of the disassembly is to shorten the disassembly time, the weight given to each side of the directed graph is time [31-33]. If the goal of the disassembly is to obtain the maximum benefit, the weight given to each side is benefit.

2.2 Modelling develop

Because the disassembly process of auto parts is influenced by many factors, it is highly uncertain. In this paper, we put forward the following assumptions:

1. Non-destructive disassembly should be used to ensure the integrity of the parts.
2. The parts need to be disassembled are regarded as rigid bodies, which will not be damaged or deformed in the process of disassembly.
3. Use one part to represent several parts which have same purposes and functions. For example, bolts, etc.
4. When the part is removed through an operation, all the constraints associated with the part should be removed.
5. When a disassembly operation is carried out, at least one part of the product should be removed from the product.

According to the degree of disassembly, the disassembly can be divided into complete disassembly, target unit/part disassembly and economic disassembly sequence. Revenues and the costs of disassembly are considered in this paper. Through establishing the disassembly network graph and the adjacency matrix, we can clear the physical and mathematical meaning of the optimization model. Then we use the linear programming to solve the optimal disassembly sequence in three ways.

$x_i (i = 1, 2, 3, \dots)$ represents whether the disassembly operation step i is executed.

$$x_i = \begin{cases} 1, & \text{execute step } i \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

For each step of operation, a parent part is disassembled into two or more than two sub parts. To ensure that only one of the ways is executed even the parent part can be disassembled in several ways, we give out the following constraints. As shown in Fig. 7, the unit "K" is obtained by disassembly operation "a", unit "K" has two disassembly ways: one is disassembled into part "U" and "V" through operation "b", the other is disassembled into part "W" and "X" through operation "c".

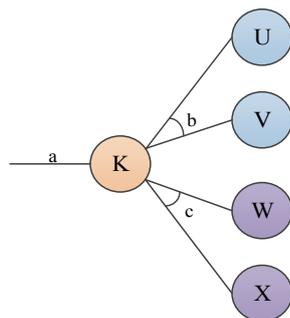


Fig. 7 Typical disassembly steps in disassembly network graph

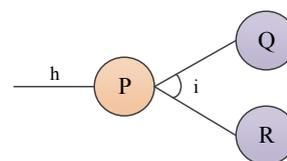


Fig. 8 Disassembly steps of unit P

So the constraint of the unit “K” is:

$$x_b + x_c \leq x_a, x_a = 1 \tag{4}$$

The sign \leq enables the occasion of “no disassembly” instead of “=”, which means that the complete disassembly sequences and selective disassembly sequences are both applied to this constraint. It is easy to conclude that for each subassembly; the node constraint can be generated, indicating that the sum of leaving flows \leq the sum of entering flows. As a result, a set of node constraints, that covers all feasible subassemblies except final subassemblies, is established. That is because final subassemblies are all single parts that need not to be disassembled further.

Once the disassembly network is established by the set of node constraints, the further task is to define the objective function. The economic benefits of the disassembly are considered in this paper. In Fig. 8, the parent subassembly “P” is obtained by operation “h” and the operation “i” is considered as an operation that destroys “P” and creates two parts “Q” and “R”. Thus the fits w_i brought by action “i”, is calculated as follows.

$$w_i = (r_r + r_q - r_p - c_i) \times x_i \tag{5}$$

where w_i is the benefits brought by operation “i”; r_r, r_q, r_p are the benefits of subassemblies “R, Q and P”, respectively. c_i is the cost of operation “i”; x_i is a binary variable that determines whether conduct the action “i”.

Thus, the objective function is the summation over all possible actions.

Model of complete disassembly

Complete disassembly is the complete decomposition of a complex product. That is, the product should be disassembled into individual part. In complete disassembly, regardless of the revenue of the disassembly, the disassembly will be carried out until the end. So the cost of disassembly is the only thing need to be considered. In this paper, the time cost of disassembly is considered as disassembly cost. So the objective of complete disassembly can be regarded as to minimize the time of disassembly:

$$\min \sum_j c_j x_j \tag{6}$$

$$s. t. \sum_j T_{ij} x_j \leq 0 \quad x_{j=1} = 1 \tag{7}$$

where c_j represents the time cost of the operation step j .

Model of optimal disassembly sequence

The disassembly for target units is carried out to obtain a certain part/unit. If removing the target parts is just to repair products, we just need to consider the disassembly time, rather than benefits. Then this optimization problem is similar to complete disassembly sequences. If the removal of waste products is to obtain the target parts, while the benefit of the other parts obtained from the disassembly process should be maximized. We need to consider the benefits and disassembly costs of the parts. Then the optimal sequence of the disassembly of the target parts can be expressed as the maximum benefit of disassembly. In the process of disassembly, the remaining parts may have lower reuse value than their disassembly costs. So in order to ensure the efficiency of disassembly, further disassembly should be stopped. We deal with the disassembly problem considering remaining values, and determine which removal steps can get the global maximum economic benefits.

$$\max \sum_i \sum_j (T_{ij} r_i - c_j) x_j \tag{8}$$

$$s. t. \sum_j T_{ij} x_j \leq 0 \quad x_{j=1} = 1 \tag{9}$$

where T_{ij} is the transition matrix; x_j is the binary variable; r_i is the benefits brought by subassembly i ; c_j is operation cost of j . $x_{j=1} = 1$ means the initial/first operation. The indexes i and j represent subassemblies and operations, respectively.

3. Floyd-Warshall algorithm

In this paper, the AND/OR graph is used to describe the disassembly process, and we make use of the conversion rules to convert the AND/OR graphs to disassembly network graphs. The process of searching for the path in the network is as same as the disassembly sequence planning.

Floyd-Warshall algorithm, which is one of the most commonly used algorithms to solve the shortest path, can find the shortest path between any two points. In Floyd-Warshall algorithm, the positive and negative values of weight w_{ij} are not limited to be positive numbers. Because of the disassembly cost is greater than the value that can be brought by the disassembly part, the benefit is negative, which means the weight of the disassembly network is negative too. So, it is feasible to use the Floyd-Warshall algorithm to solve the problem of disassembly sequences planning. The steps of the Floyd-Warshall algorithm are summarized as follows:

Step 1: Input weight matrix W , seek the shortest path from point v_r to point v_j ($j = 1, 2, 3 \dots$).

Step 2: Make $l_{rj}^{(k)}$ restore the shortest path from point v_r to point v_j within k steps. So $l_{rj}^{(1)} = w_{rj}$.

The path from v_r to v_j within k steps can be divided into two parts: from v_r to v_i within $k-1$ steps, the shortest path is $l_{ri}^{(k-1)}$; from v_r to v_j within one step, the shortest distance is w_{ij} .

$$l_{ij}^{(k)} = \min_{1 \leq i \leq n} \{l_{ri}^{(k-1)} + w_{ij}\} \tag{10}$$

$$l_k = (l_{r1}^{(k)}, l_{r2}^{(k)}, \dots, l_{rn}^{(k)})^T \quad (K = 1, 2, \dots) \tag{11}$$

According to the Eq. 11, the i^{th} element $l_{ri}^{(k)}$ in the column matrix l_k is the minimum of the sum of the i column $(w_{1i}, \dots, w_{ni})^T$ in the weight matrix W and the corresponding elements of row $l_{ri}^T (l_{r1}^{(k-1)}, l_{r2}^{(k-1)}, \dots, l_{rn}^{(k-1)})$.

$$l_k^T = l_{k-1}^T \times W \tag{12}$$

Step 3: When all $w_{ij} \geq 0$, the shortest path from v_r to v_i does not repeat (no circle). Since there are n nodes in the network, $n - 1$ steps are needed at most from v_r to v_i in the shortest path. If the shortest path contains n steps, we must repeat one step at a certain point, which makes it the same as the shortest path with $n - 1$ steps. So we have:

$$l_n = l_{n-1} \tag{13}$$

Step 4: After $n-1$ times multiplication of the matrixes, the shortest paths from v_r to each point can be found. When $l_k = l_{k-1}$ appears in the calculation process, we can find it consistent with the shortest distance of walking $k-1$ steps and k steps, then the calculation can be ended.

In this paper, the Floyd-Warshall algorithm is introduced to solve the problem of disassembly sequences planning for automotive products, and the optimal product disassembly sequence is obtained:

Step a: If the shortest time of disassembly is the target, the weight adjacency matrix W_t for the time of the disassembly should be put into the program. If obtaining maximum benefit of disassembly is the target, the weight adjacency matrix W for the benefit of disassembly should be put into the program.

Step b: Set $k = 1$, and the original vehicle as a starting point v_r of disassembly. Secondly, calculate the shortest distance $l_1^k = w_{r,j}$ from v_r to the disassembly state $v_j(j = 1,2,3, \dots, n)$ after one operation step.

Step c: Set $l_k^T = l_{k-1}^T \times W$ or $l_k^T = l_{k-1}^T \times -W$, $k = 2,3,4 \dots$ then calculate the shortest distance l_k^T to the disassembly state $v_j(j = 1,2,3, \dots, n)$ within at most k operation steps.

Step d: Confirm whether the equation $l_k^T = l_{k-1}^T$ is correct. If the equation is satisfied, then the algorithm ends, and we can get the product sequence. Otherwise, return to Step c.

In order to describe the application of the algorithm in this problem, the design procedure of the Floyd-Warshall algorithm is used to optimize the complete disassembly sequence of the piston connecting rod based on the benefit adjacency matrix in Sec. 2. The benefit adjacency matrix of the piston connecting rod group is assumed as follows:

$$W = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{matrix} & \begin{vmatrix} 0 & 7 & 6 & \infty & \infty & \infty & \infty & \infty \\ \infty & 0 & \infty & -2 & \infty & \infty & \infty & \infty \\ \infty & \infty & 0 & 1 & \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & 0 & 2 & 3 & \infty & \infty \\ \infty & \infty & \infty & \infty & 0 & \infty & -1 & \infty \\ \infty & \infty & \infty & \infty & \infty & 0 & -4 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 0 & 3 \\ \infty & 0 \end{vmatrix} \end{matrix}$$

The optimized complete disassembly sequence is 1-3-4-5-7-8, as shown in bold path in Fig. 9. The maximum benefit of this disassembly sequence is 11.

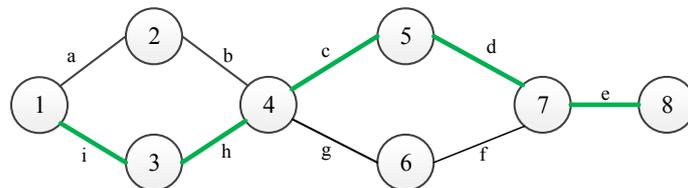
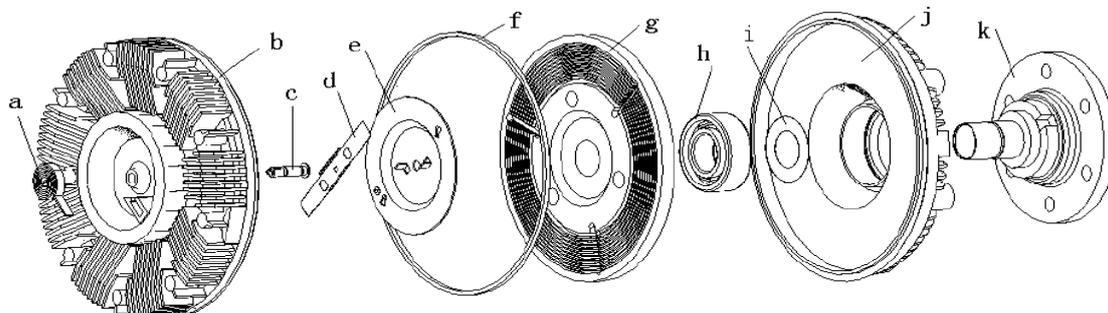


Fig. 9 The complete disassembly sequence of the piston connecting rod group

4. Case study

In order to verify the feasibility and effectiveness of the application of disassembly model based on the AND/OR graph in disassembly sequence planning, the silicon oil fan clutch is taken as an example depicted in Fig. 10. According to the connection relation and precedence relation between the silicone oil fan clutch parts, the disassembly AND/OR graph is obtained after analysis. As shown in Fig. 11.



a: Bimetallic strip temperature sensor; b: Clutch front cover; c: Valve shaft; d: Valve; e: Partition; f: Seal ring; g: Active plate; h: Bearing; i: Shim; j: Clutch rear cover; k: Drive shaft

Fig. 10 Silicon oil fan clutch assembly explosion diagram

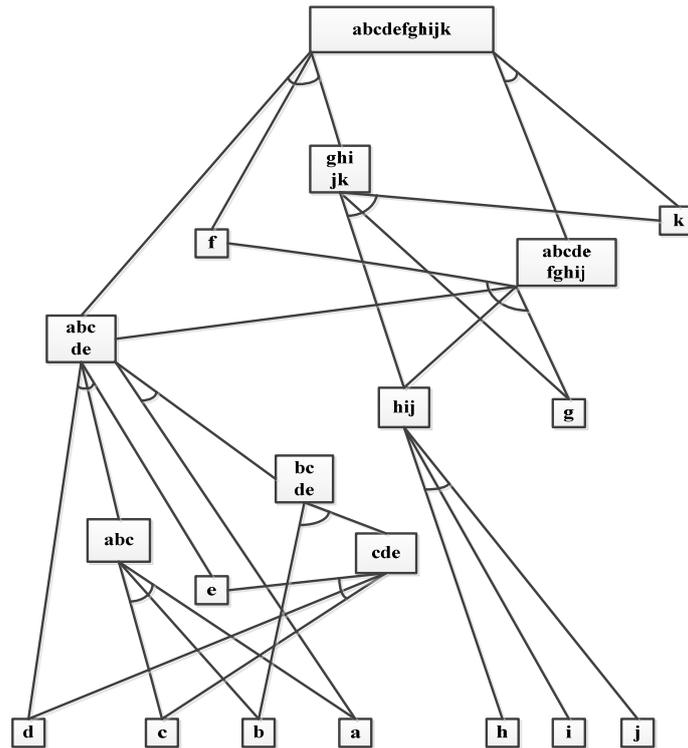


Fig. 11 The AND/OR graph model of silicon oil fan clutch disassembly

According to the rules between the disassembly AND/OR graph and the disassembly network graph, the AND/OR graph model of the silicon oil fan clutch are transformed and simplified to Fig. 12. The disassembly path of the silicon oil clutch is represented by the network.

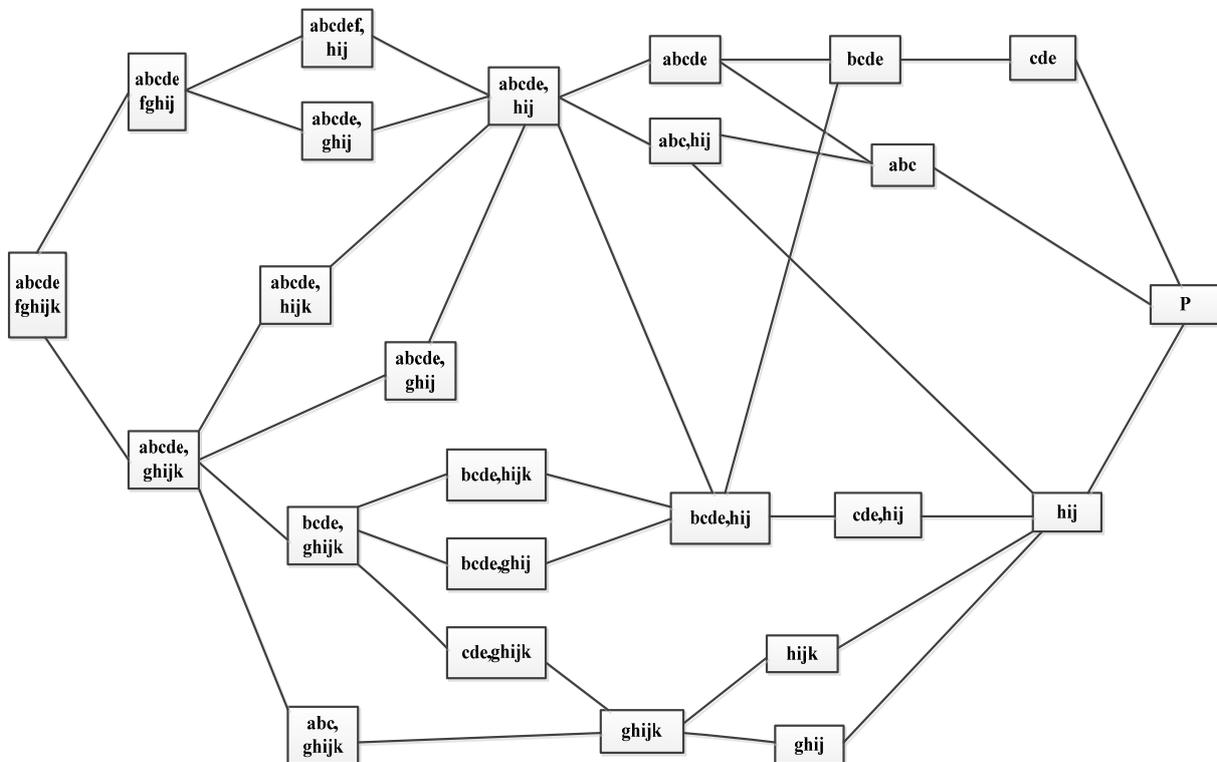


Fig. 12 The disassembly network diagram of silicone oil fan clutch assembly

The nodes in Fig. 12 are numbered for simplification as shown in Fig. 13. Number “1” is the original silicone oil clutch, while number “11” is the completely disassembly state of a silicon oil clutch. Other numbers are the states that may exist in the disassembly operation. Separate the different units in a node with a comma. For example, the node “bcde, hij” consists of two parts: the unit “bcde” and the unit “hij”.

Assume that the disassembly process of the silicon oil fan clutch is linear. In order to simplify the model, this paper only considers the time consumed by the disassembly process and the benefits of disassembly parts. The disassembly sequence planning is studied according to the disassembly network graph model.

First, we need to obtain the relevant data about the recovery value of all parts and units in disassembly operations. The relevant data is obtained according to the actual disassembly experience.

According to practical experience, the time adjacency matrix W_t of disassembly network graph is obtained. The demolition time for each disassembly operation and while the benefit adjacency matrix W of disassembly network graph can be attained accordingly.

Based on the data above, the Floyd-Warshall algorithm is used to solve the optimal sequence of the complete disassembly, the optimal sequence of the disassembly of the target unit, and the economic optimal disassembly sequence of the silicon oil fan clutch.

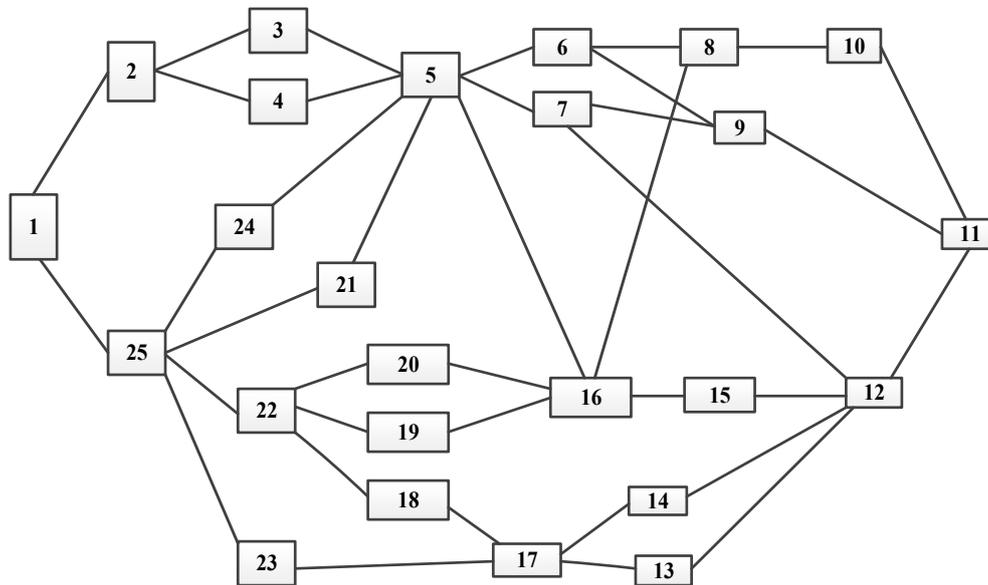


Fig. 13 The disassembly network diagram silicone oil fan clutch

4.1 The optimal sequence of the complete disassembly

We do not need to consider the effectiveness of the disassembly parts in complete disassembly, just need to consider the minimum disassembly cost. That is, the time of disassembly should be the least. Use the Floyd-Warshall algorithm to calculate the shortest path from node “1” to node “11”. The shortest time of complete disassembly is 32, corresponding to the complete disassembly is: 1-25-21-5-7-9-11 (Fig. 14).

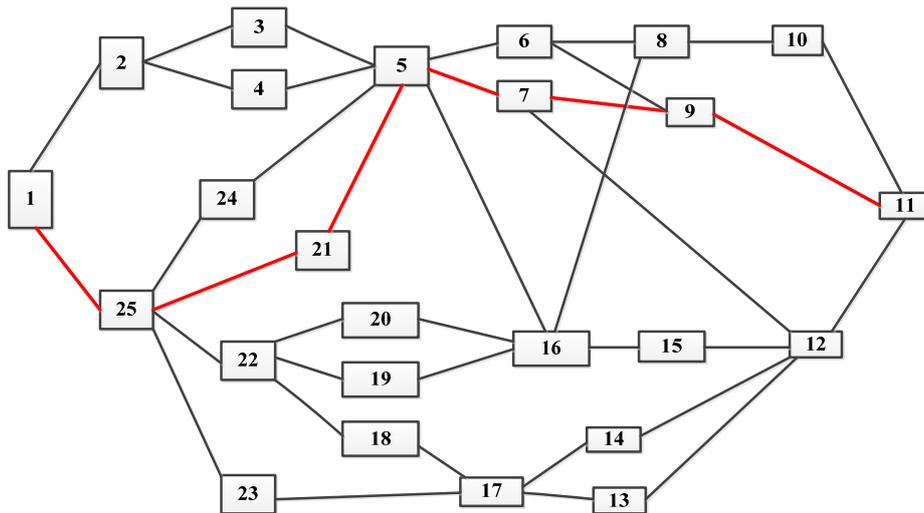


Fig. 14 The complete disassembly sequence path

4.2 Optimal sequence for disassembly of target units

Since the case is the disassembly of the target unit in the silicon oil fan clutch, and aim to maximize the benefits of disassembly while ensuring obtaining the target units successfully. Node “16” in Fig. 15 is the objective state. Calculate the shortest path from node “1” to node “16”. The optimal sequence is: 1-25-21-5-16 (Fig. 15), while the maximum benefit to the objective state is 81. The final state of disassembly is: part f, part k, part g, part a, unit “bcde”, unit “hij”.

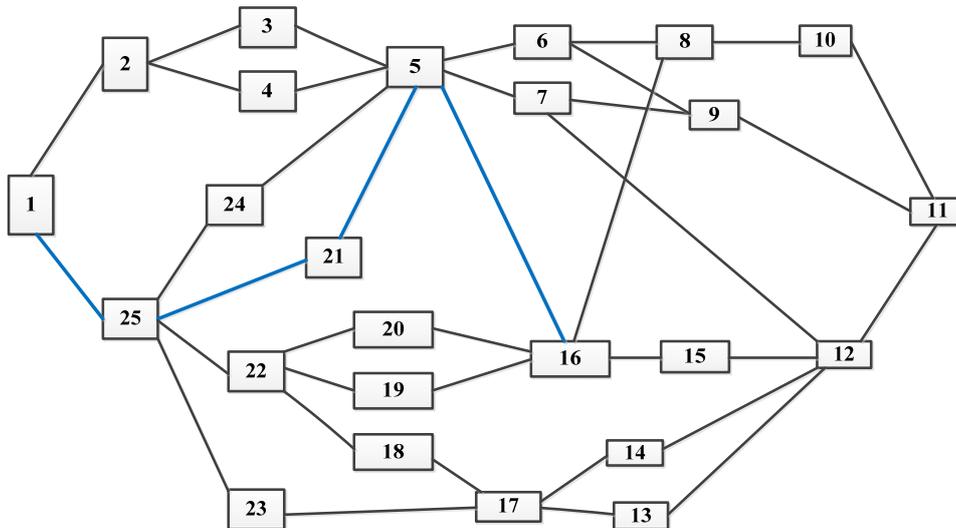


Fig. 15 Optimal sequence of disassembly of target units

4.3 Economic optimal sequence

The economic benefit of disassembly is the difference between the economic value of disassembled parts and the cost of disassembly process. While a products is disassembled to a certain extent, and the residual part recovery value is less than their disassembly cost, then further disassembly is unnecessary. In order to determine the economic optimal sequence of the silicon oil fan clutch, we need to calculate the benefits of node “1” to other nodes through the benefit adjacency matrix, and find the maximum benefits of them. The node of the maximum benefit is the end of the demolition operation. The benefit of node “1” to each node is shown in Fig. 16.

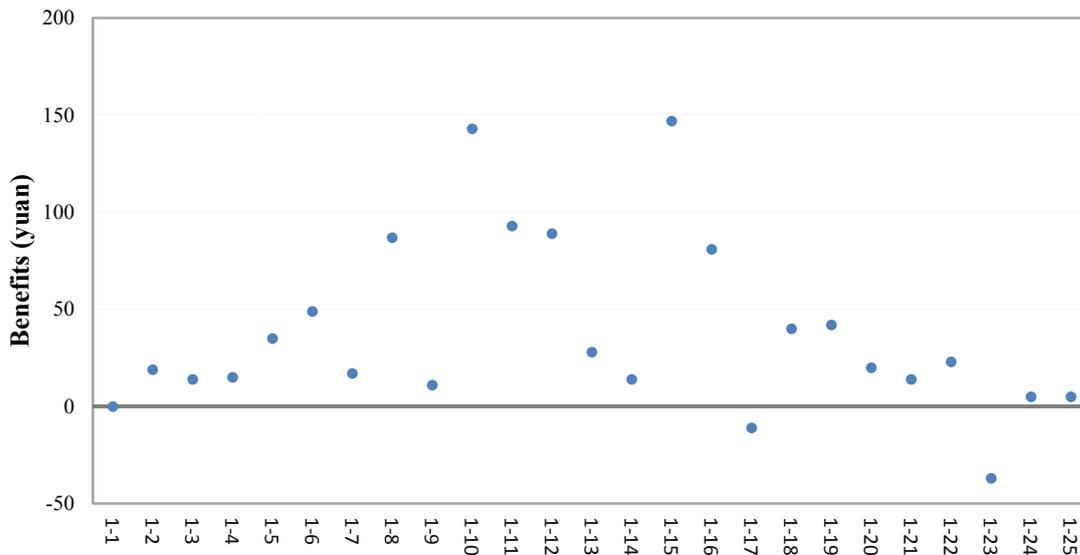


Fig. 16 Benefits of node 1 to each node

From Fig. 16 we can see that the maximum benefit appears at 1-15. That means when the silicon oil fan clutch is removed to the state of node “15”, the benefit of the whole disassembly is maximum, and the maximum benefit is 147. Economic optimal sequence is 1-25-21-5-16-15 (Fig. 17). The final state of disassembly is: part f, part k, part g, part a, part b, unit “cde”, unit “hij”.

By solving the optimal sequence of the above three kinds of disassembly methods, we verify the effectiveness of the disassembly network model and the Floyd-Warshall algorithm proposed in this paper for the disassembly sequence planning of silicon oil fan clutch. This paper improves the efficiency and efficiency of disassembly, and presents a new way of thinking for the disassembly sequence of automobile parts.

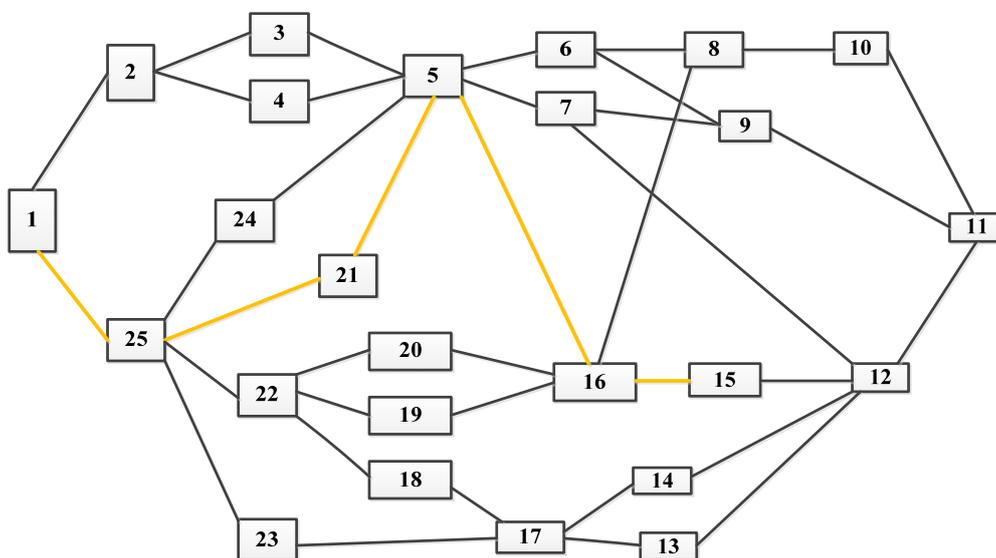


Fig.17 Economic optimal sequence

5. Conclusion

Disassembly and recycling of industrial products are one of the effective methods for resource conservation and environment protection. Reasonable disassembly planning helps to improve the disassembly efficiency and reduce the cost and time of disassembly. In this paper, the disas-

sembly sequence of automobile parts is studied. We propose the model of disassembly network based on the idea of the AND/OR graph. The transition matrix is used to describe the constraint relations between parts and units, while the weight adjacency matrix is used to describe the cost and benefit in disassembly operations. The disassembly sequence planning problem is solved by the classic Floyd-Warshall algorithm. The feasibility of the model and algorithm are verified by solving the optimal sequence of three different disassembly purposes. In this paper we consider the time and benefits of disassembly, but there are a lot of factors affect the disassembly efficiency in manufacturing. In the future, we will improve the model by considering more factors such as the direction of the demolition and the energy consumption. This approach could be applied to obtain optimum disassembly sequence of products containing complex AND/OR hierarchical relationships such as airplanes, automobiles and industrial machinery.

Acknowledgement

This work was supported in National Natural Science Foundation of China 71571026 and 51578112, Liaoning Excellent Talents in University LR2015008, and the Fundamental Research Funds for the Central Universities (YWF-16-BJ-J-40 and DUT16YQ104).

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