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Research of Partial Destructive based Selective Disassembly Sequence Planning

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Abstract: In the process of recycling EOL (end of life) products, disassembly is an important stage. Moreover, there are several targets for disassembly: reuse, remanufacturing and material recycling. In order to improve the efficiency of disassembly, only the component which need to be reused or remanufactured need to be disassembled with non-destructive method. The rest components which recycled for material can be disassembled with partial destructive method. Namely, partial destructive disassembly is more practical than total disassembly within recycling process for EOL products. In this paper, the generally used partial destructive disassembly methods are analyzed. And several rules are defined for reconstructing the hybrid graph of EOL product. And then, an extended Floyd algorithm is proposed for searching optimized disassembly sequence. With this algorithm, the material properties of parts, connection properties between parts or components are taking into account. By ranking the cost of several possible disassembly path, the optimal disassembly sequence is obtained for target component. At last, a soybean milk machine is used as a study case to verify the former approach.

Keywords: End of life product, partial destructive disassembly, selective disassembly.

1. INTRODUCTION

With the development of modern society, the non-reasonable treatment of EOL products is affecting the natural environment more and more than before. If new technology and approach can be applied on the recycling of EOL products, not only the impacts on environment can be greatly decreased, but also consumption of natural resources is significantly reduced. While in the disposal of EOL products, disassembly is an important stage. Reasonable and efficient disassembly will not only increase the reuse rate of components and parts, but also reduce the final residue for landfill.

Currently, there are many research work have been done on the disassembly theories, but most of them are carried out based on the non-destructive mode [1-5]. However, for EOL mechanical and electrical products, non-destructive disassembly is not only difficult to perform, but also totally unnecessary. Since the recycling of EOL products, most of the parts or components are transformed into raw materials and reused in the manufacturing. For this circumstance, partial destructive method does not have any influences on material reuse. For this purpose, Klaus *et al*. presented that the fasteners can be removed by destructive method in order to improve the efficiency of disassembly [6]. Kyung *et al*. introduced a disassembly tool based on the impact principle for cutting screw [7]. John *et al*. designed a semi destructive tool which used on the industry robot for disassembly [8]. Kyonghun *et al*. present a design for disassembly (DFD) method, the destructive disassembly is considered in the virtual prototype [9]. Song *et al*. study the influence of partial destructive on the disassembly planning, but the method of destructive disassembly is not take into account [10].

In this paper, the target of selective disassembly is to separate the component for reuse or remanufacturing. The rest of the components or parts can be separated by partial disassembly method, such as shearing, cutting or riving off. And all the rest components can be disposed by shredding and sorting technology. By this means, the revenue of recycling of EOL products will be improved. In the mean time, the efficiency of disassembly also increased.

2. DISASSEMBLY MODELING BASED ON THE HYBRID GRAPH AND PARTS PROPERTIES

2.1. Hybrid Graph for Disassembly Modeling of EOL Product

Prior researchers have presented many representation methods for modeling of EOL product, including undirected graph, directed graph, And-Or graph and Petri net etc. [11]. All these method have their own advantage and disadvantage within modeling and searching of disassembly sequence. Among them, the hybrid graph is more suitable for modeling structure of EOL product, especially for selective disassembly. Since hybrid graph of EOL product consist of

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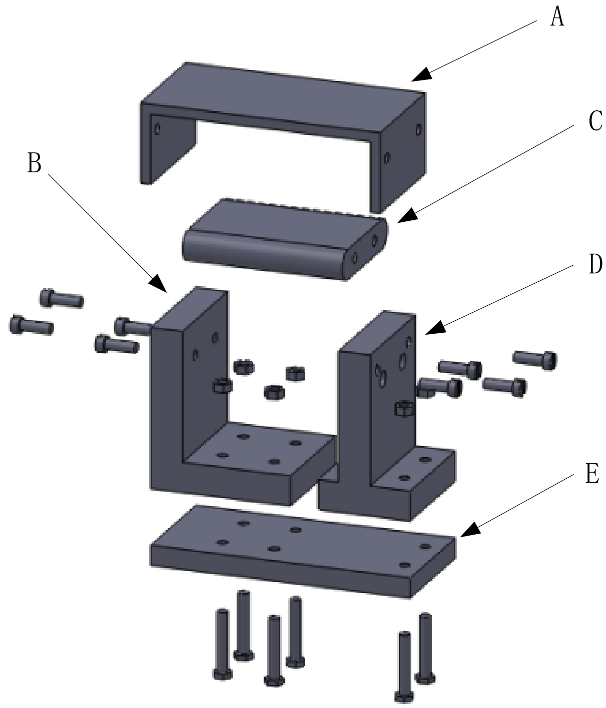

Fig. (1). Structure of sample EOL product.

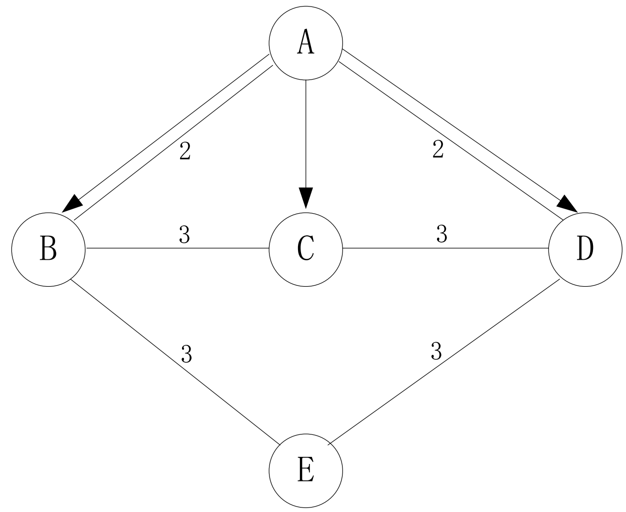

Fig. (2). Hybrid graph of sample EOL product.

undirected graph and directed graph, which used to represent the connection between the parts and the precedence relationship, respectively.

Take the EOL product as shown in Fig. (**1**) as example, the corresponding hybrid graph is illustrated in Fig. (**2**). The character which closed by a circle denote the part or component. The undirected edge (connection line with no arrows between two parts) denote the contact relationship between two parts. The directed edge denote the precedence relationship. For example, in order to separate part B, C and D, part A should be removed firstly. That is, there exist precedence among part A and part B, part A and part C, part A and part D. So, there are directed edges exist from A to B, C and D.

In detail, in the process of modeling hybrid graph, undirected edge can be created by computer program according to the assembly information in 3D CAD model of EOL product. While directed graph, i.e. precedence information need to be defined manually. Because directed graph is used to describe the obstacle relationship between parts, and it is difficult for computer to solve this problem.

Table 1. Parts properties.

Part Name	Material	Material Strength	Recycling Purpose
A	Plastic	Weak	Material recycling
B	Cast iron	Strong	Material recycling
C	Copper	Strong	Remanufacturing
D	Cast iron	Strong	Material recycling
E	Cast iron	Strong	Material recycling

In order to modeling EOL product for disassembly, it is not enough just consider the geometric information. The material properties and connection properties also should be incorporated into the modeling of disassembly. Parts properties of sample product in Fig. (**1**) are listed in Table **1**. The third column represent the material strength with linguistic variable. Table **2** list the connection properties of same product. The fifths column is used to describe the joint strength with linguistic variable according to the fuzzy cost model of disassembly [12]. The sixth column is the corresponding fuzzy number of linguistic variable. Note that, this fuzzy number also marked in the Fig. (**2**).

2.2. Quantitative Model of Hybrid Graph

According to graph theory, quantitative model of hybrid graph can be represented by adjacent matrix *Gc* and

Table 2. Connection properties.

No. of Connection	Associated Part 1	Associated Part 2	Connection Properties	Joint Strength	Fuzzy Number
1	A	B	Screw M4×2	Weak	2
2	A	D	Screw M4×2	Weak	2
3	B	C	Screw M8×2	Strong	3
4	C	D	Screw M8×2	Strong	3
5	B	E	Screw M10×4	Strong	3
6	D	E	Screw M10×2	Strong	3

precedence relationship matrix *Gp*. Where undirected graph is described with *Gc*. The element of *Gc* denote the connection between parts, e.g. $r_{0,1}$=1 denote that part 0 and part 1 is connected together by a certain assembly method. While if $r_{0,1}$=0, which means that there is no assembly relationship exist between part 0 and part 1. In this paper, the meaning of the element r is extended. It is not only used to describe the assembly information, but also used to describe the joint strength of connection, i.e. fuzzy number in Table **2** is used here as the element of *Gc*. As diagonal elements of *Gc* represent the relationship between the part and itself, thus its values are all 0.

$$Gc=\begin{bmatrix} 0 & r_{0,1} & \cdots & r_{0,n-1} \\ r_{1,0} & 0 & \cdots & r_{1,n-1} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n-1,0} & r_{n-1,1} & \cdots & 0 \end{bmatrix} \quad Gp=\begin{bmatrix} 0 & p_{0,1} & \cdots & p_{0,n-1} \\ p_{1,0} & 0 & \cdots & p_{1,n-1} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n-1,0} & p_{n-1,1} & \cdots & 0 \end{bmatrix}$$

Precedence relationship matrix *Gp* used to describe the direct graph of hybrid graph. That is, the precedence relationship of disassembly model of EOL product. where $p_{i,j}$ denote that part i (in the horizontal direction of matrix) has a precedence to part j (in the vertical direction of matrix). *Gp* of Fig. (**2**) is as follow.

$$Gp=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

According to the above mentioned adjacent matrix *Gc* and precedence relationship matrix *Gp*, the disassembly sequence can be decided by searching and judging the element of *Gc* and *Gp*. Firstly, the possibility of operation should be detected according to matrix *Gp*. By calculating the summary of each row of *Gp* (Equation 1), if summy of row(j) equal 0 then part j can be disassembled.

$$\sum_{i=1}^{n} p_{i,j}=0 \quad (1)$$

And then, by searching matrix *Gc*, the suitable disassembly operation can be determined. By calculating the summary of row(i) in *Gc* (Equation 2), the operation of disassembly can be determined. Value of summary greater than 0 means that there are several connections need to be disassembled. Otherwise, if its value equal to 0, which means that there is no connection need to be operated for disassembly. Currently several algorithm have been presented for solving suitable disassembly operation according to quantitative model of hybrid graph [13-15].

$$\sum_{i=1}^{n} r_{i,j}\geq 0 \quad (2)$$

After a part or component is detached, the corresponding information should be removed from *Gc* and *Gp*. That is, number of elements in *Gc* and *Gp* is changed. New matrix of *Gc* and *Gp* needed to be recomposed by subtract the element which have been detached.

3. SELECTIVE DISASSEMBLY STRATEGY BASED ON THE PARTIAL DESTRUCTIVE DISASSEMBLY

3.1. Partial Destructive Disassembly Method

For the aim of employing partial disassembly method within disassembly process, the generally used tools and operation should be analysed.

3.1.1. Breaking with Brittle Part

This method are often used in dismantling of part or component which made of plastic or other brittle material, such as automotive interior parts, housing of washing machine and etc. Using specially designed tools, components can be break easily instead of disassembling all the screws manually one by one. Certainly, to carry out this method, the part or component should be disassembled for material usage.

3.1.2. Fasteners Cutting

For this instance, a special hydraulic or electric driven cutting tool is used to cut the nuts of bolts. By this means, the efficiency of disassembly is increased. Meanwhile, the commonality of the tools is greatly improved. Because the workers are no longer need to change the tools for each operation. For the screw instance, the head of the screw also can be cut off by this tools directly.

3.1.3. Shearing or Cutting with Subordinate Part

In the structure of EOL products, some of the parts are in the shape of rob, link or tube. By using hydraulic or electric driven cutting tool, structure of EOL product can be detached more easy than separating all the parts or components one by one. For instance, in the process of disassembly trunk lid of end of life vehicle. Cutting the link between the lib and the body only cost few time compared with ordinary method.

With this approach, sometimes not only the operating time is decreased, but the number of connection in EOL product also decreased. For instance, in the structure as shown in Fig. (**3**), if part C is cut into two section, the connections between A and C, B and C are need not be detached. Thus, the number of connection is reduced.

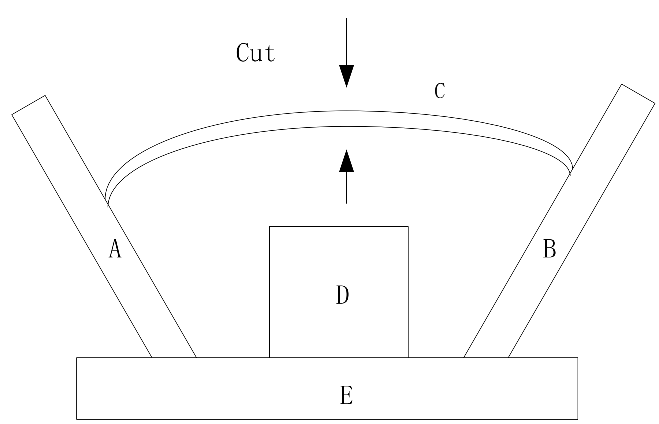

Fig. (3). Cutting subordinate part.

3.2. Rules for Partial Destructive Disassembly

According to former analysis, corresponding rules of partial disassembly are defined as follow. The hybrid graph of EOL product can be recomposed based on this rules.

Rule 1: If one of the part in structure made of brittle material, and its recycling target is material usage. then suitable tool can be choosed to break the connection of this part. Yet, in this circumstance, the special designed tool is a significant factor for partial disassembly.

Rule 2: if two or more parts are connected with bolts or screws, and the specification exceeds the threshold value (small screw or bolt is not suitable for detaching with hydraulic tool). Then a special tool can be used to break the nuts or bolts for breaking the connection quickly. By this means, the value of disassembly cost in the hybrid graph of EOL product is transformed into a new one.

Rule 3: if one part in the structure of EOL product is in the shape of rob, link or tube, and its recycling target is material usage, then a special tool can be used to cut or shear the part. Significantly, by this means, the structure of hybrid graph is changed. The adjacent connections are transformed into one connection, the value of disassembly cost also changed.

3.3. Reconstructing Hybrid Graph Based on the Rules of Partial Destructive Disassembly

According to former rules, initially composed disassembly model can be transformed into a new one. Take EOL product in Fig. (**1**) as an example, part A made of plastic and can be treated as rule 1. Part B and part D are connected with part A by bolts, there nuts can be break by hydraulic tool according to rule 2. Note that, there are 4 bolts in the connection of A and B, while there are 2 bolts in the connection of A and D. Namely, the cost value of partial disassembly is different. The recomposed hybrid graph is illustrated in Fig. (**4**).

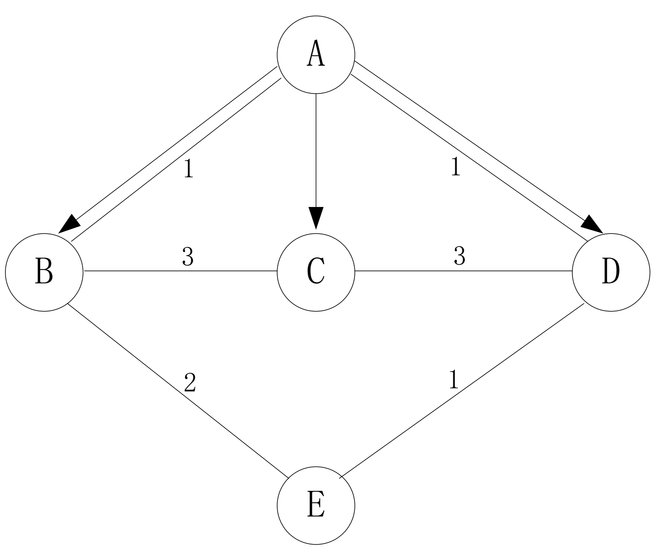

Fig. (4). Recomposed hybrid graph based on partial destructive disassembly.

3.4. Floyd Algorithm Based Selective Disassembly Sequence Planning

According to the rules of partial destructive mode mentioned above, a searching process for selective disassembly is proposed in the following section. Although there are many intelligent algorithms have been applied on this problem, most of them are focused on the local optimization. In this paper, we present a Floyd algorithm based searching method for partial destructive based disassembly process planning. Because searching of optimized disassembly sequence is actually a shortest path searching problem. And the Floyd algorithm is the more efficient method for this issue.

For the aim of detaching target part or component in EOL product, usually we can not separate the target part by just one operating sequence in the hybrid graph. As shown in Fig. (**5**), if we want to separate the part C from the EOL product, the connection between A and C, B and C should be detached together. Hence, the condition of LSP (list of separating part) is defined to describe the parts which contact with the target part and its connection should be detached. The LSP in Fig. (**5**) is (A, B). Part A and part B should be operable for disassembly, but not necessary for remove from the EOL product. Thus part C can be removed.

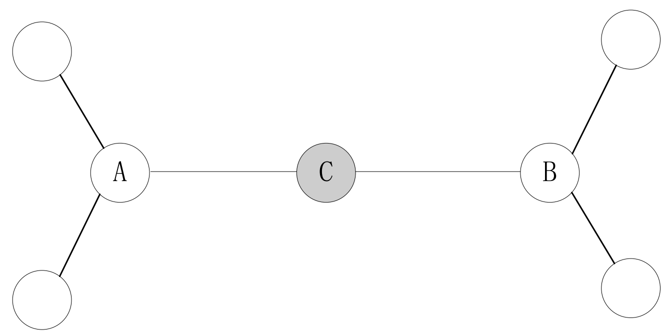

Fig. (5). Principle of separating target part.

To carry out a disassembly work of EOL product, we usually start from the outside of EOL product. Because of the constraint of connection, only several parts or components are feasible for disassembly. This parts or components are defined as entrance parts. A list E_i also defined for this information. Especially, the entrance part in hybrid graph is the start point for Floyd algorithm.

Whole searching algorithm is illustrated in Fig. (**6**). In the beginning, relevant data are input for composing hybrid graph with non-partial disassembly. And then, the data structure of new hybrid graph is created based on the rules of above presented partial disassembly. It should be noted that, in this section several additional rules and information are needed for calculating. Especially a predefined rule for parts combination is needed. For example, if connected two parts are made of the same material and recycled for usage of material. Thus two parts can be combined with one part. By this means, the new hybrid graph is simplified.

According to the data of new hybrid graph based on the rules of partial disassembly, the searching algorithm is executed mainly based on the Floyd algorithm. Firstly an

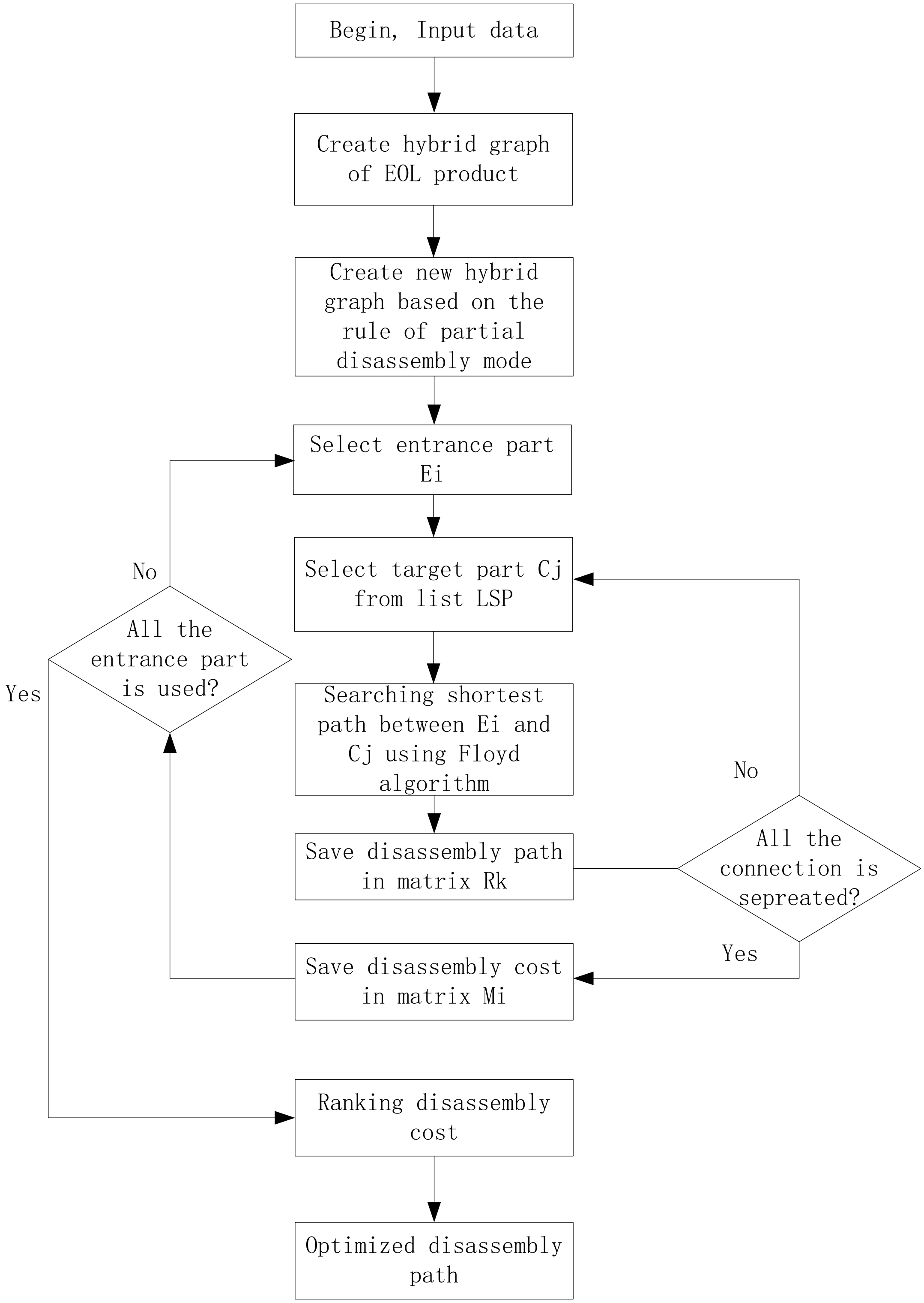

Fig. (6). Algorithm for searching optimized disassembly sequence.

entrance part is selected from the list of Ei as start point. And then, another part is selected from the list of LSP for terminal point. With Floyd algorithm a shortest path can be determined by calculating all the disassembly cost by fuzzy theory. After this step, a judgment will be executed with condition of separation of target part. If condition is satisfied, namely, all the connections of target part have been detached, the data of path and cost are stored in the matrix Mi. While if condition is not satisfied, then another part in the LSP will be selected. For a certain entrance part, usually there are several parallel paths exist for remove the target part. After all the disassembly path based on a certain entrance part have been determined. A judgment of entrance part will also be executed. If all the entrance part is used, then the ranking of all the disassembly sequence can be carried out. Otherwise, if there are some entrance parts are not used, the next entrance part will be selected for next start point until all the entrance parts are used. At last, by comparing all the disassembly sequence, an optimized disassembly sequence will be determined with lowest disassembly cost.

4. A CASE STUDY

A household soybean milk machine is taken as an example to analyze the feasibility of above mentioned approach. As barrel part of the soybean milk machine can be separated directly, we only focus on the disassembly and recovery of the head of machine. The structure of head is shown in Fig. (**7**). Within the head part of the soybean milk machine, only the electric motor is valuable for remanufacturing and need to be disassembled with a nondestructive method. The temperature sensor and heater also need to be disassembled and disposed separately for material recycling as there are small amount of precious metals in its. Hence, the electric motor, heater and temperature sensor are defined as the target of selective disassembly. The rest of the parts are all disassembled for material recycling. That is, the partial destructive disassembly method can by adopted on them. The material properties and recycling target are listed in the Table **3**.

Firstly, the hybrid graph of head of soybean milk machine is created as shown in Fig. (**8**). According to the partial destructive disassembly rules in section 2, wire 4,5,6 and 7 can be disposed with controlling board as electric waste, and its can be disassembled by cutting method easily. So, rule 3 can be used for wire 4,5,6 and 7. Thus by this means, after partial disassembly operation, wire 4,5,6 and 7 are combined to the controlling board, i.e. part 2. And then, the upper cover and lower cover are made of plastic and disassembled for material recycling. The rule 1 can by applied on them. By this method, the disassembly cost can be reduced. At last, the reconstructed hybrid graph is illustrated in Fig. (**9**).

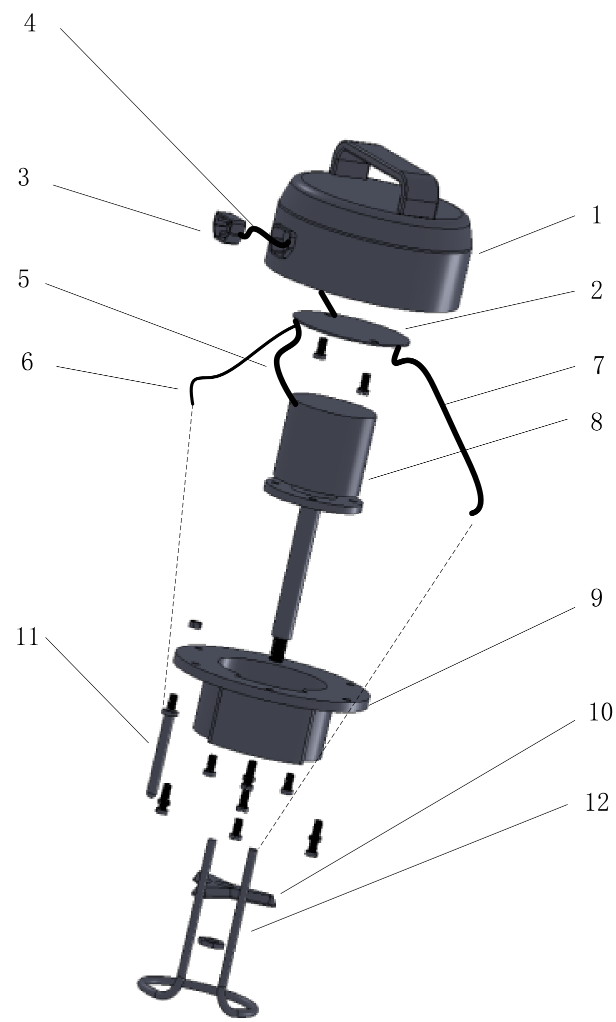

Fig. (7). Structure of head of soybean milk machine.

Table 3. Part information of soybean milk machines.

S/N	Part Name	Material	Recycling Target
1	Upper cover	Plastic	material recycling
2	Controlling board	Epoxy resin, cooper and ceramics etc.	Precious-metals recycling
3	Power socket	Plastic, copper	material recycling
4	Lower cover	Plastic	material recycling
5	Connection wire	Plastic, copper	material recycling
6	Connection wire	Plastic, copper	material recycling
7	Connection wire	Plastic, copper	material recycling
8	Motor	Silicon steel, copper	Remanufacturing
9	Lower cover	Plastic	material recycling
10	Blade	Stainless steel	material recycling
11	Temperature sensor	Copper, semiconductor materials	Precious-metals recycling
12	Heater	Nickel chromium alloy, copper	Precious-metals recycling

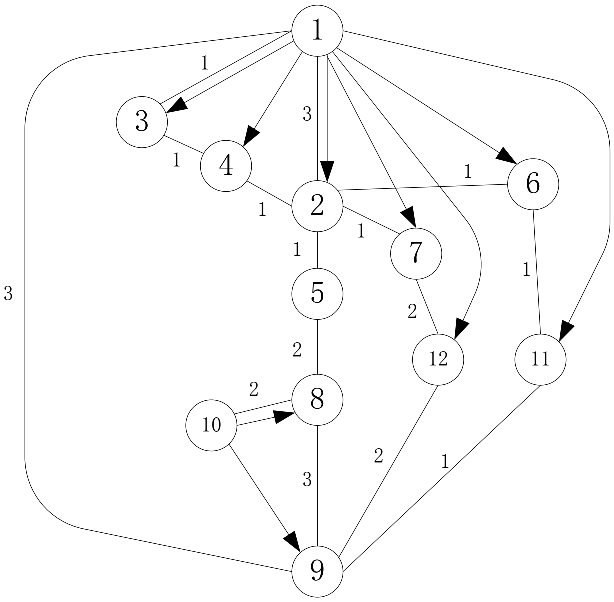

Fig. (8). Hybrid graph of soybean milk machine head parts.

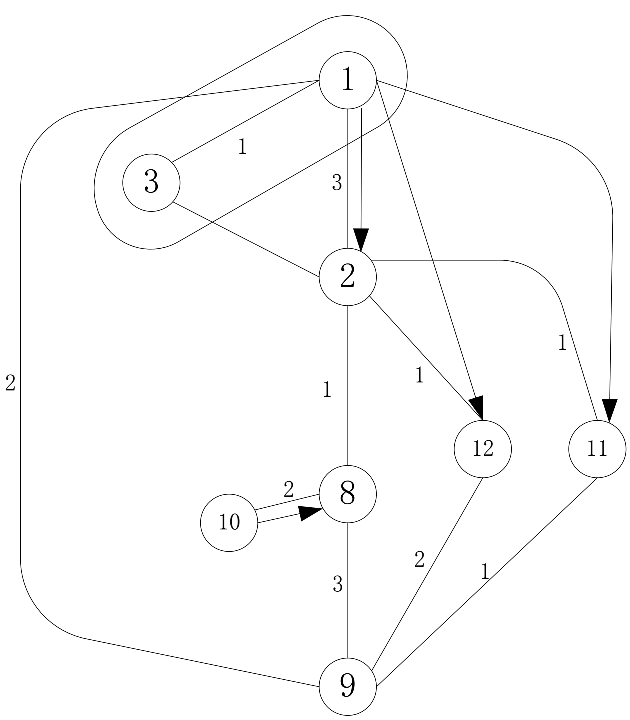

Fig. (9). Re-composed hybrid graph based on the rule of partial disassembly.

According to principle of selective disassembly, not all the parts should be disassembled separately except target component. In the head of soybean milk machine, part 3, i.e. electrical outlet mainly composed of plastic material and several small parts made of copper. It can be disposed with upper cover by shredder and sorting technology. Thus, it can be combined with the part 1. So, the Fig. (**9**) can be further recomposed into Fig. (**10**).

Corresponding adjacent matrix *Gc* and precedence relationship matrix *Gp* of Fig. (**10**) are as follows:

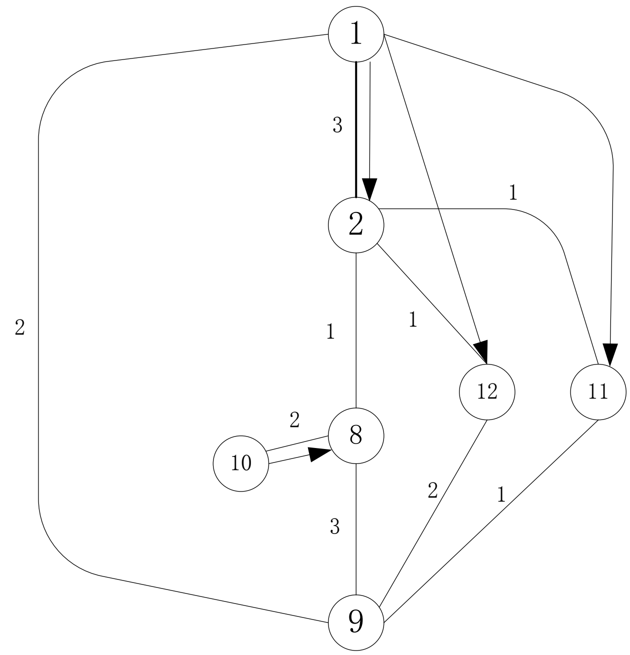

Fig. (10). Hybrid graph after several parts are combined together.

$$G_c = \begin{bmatrix} 0 & 3 & 0 & 3 & 0 & 0 & 0 \\ 3 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 3 & 2 & 0 & 0 \\ 3 & 0 & 3 & 0 & 0 & 1 & 2 \\ 0 & 0 & 2 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 2 & 0 & 0 & 0 \end{bmatrix} \quad G_p = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

After analyzing and calculating the disassembly process of the soybean milk machine components according to the above mentioned algorithms and relevant rules, the disassembly sequence to separate motor, heater and temperature sensor is:

(1-9), [(2-8), (2-11), (2-12)], [(9-8), (10-8)]

In the above sequence, sign "()" represents the disassembly operations of connections between two parts. Where [(2-8), (2-11), (2-12)] indicates that the three disassembly operations are equal in sequence with the same disassembly costs.

CONCLUSION

Within recycling oriented disassembly, not only the geometry properties of connections should be considered, but also the economic and efficiency should be considered. It is nonsensical to disassembly all the parts or components with non-partial approach. The recycling target of parts or components should be take into account, reuse, remanufacturing, material usage. With special tools, some of the connections can be detached by partial disassembly method easily. On one hand, the cost of disassembly for EOL product is reduced. On the other hand, the technical difficulty also reduced. In this paper, generally used partial disassembly method is analyzed. Especially, the corresponding rules are defined for recomposing hybrid graph of EOL product. Furthermore, a Floyd algorithm based searching approach is proposed. This will help to find an optimized disassembly sequence.

Certainly, in the actual disassembly work, the partial disassembly approach is not limited in the scope of this paper. That is, new partial disassembly methods, new partial disassembly tools, and new rules also should be studied in the future work.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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