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Title page

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ORIGINAL ARTICLE

Objective disassembly sequence planning of used mobile phones based on improved hybrid graph disassembly model

Feng-Fu Yin¹ • Xiao-Dong Wang¹ • Hong-Rui Li¹ • Hua-Dong Sun¹ • Sui-Ran Yu² • Lin Li¹

Abstract: To solve the problems of environmental pollution and waste of resources caused by used mobile phones, the study of objective disassembly sequence planning is carried out for used mobile phones. In view of the connection of mobile phone parts with multiple parts and the need to disassemble components, the concepts of containment, exclusion, and components are integrated into the hybrid graph. An improved hybrid graph is proposed and the improved hybrid graph disassembly model suitable for mobile phone disassembly is established. The ant colony algorithm is used to search for the optimal disassembly sequence, with the objective of minimum disassembly time. Finally, the improved hybrid graph disassembly model is applied to obtain the disassembly solution of HUAWEI Honor 6. The experimental results demonstrate that the disassembly sequence generated by the improved hybrid graph disassembly model can describe the actual disassembly process of disassembling components with less disassembly time.

Keywords: Improved hybrid graph • Used mobile phones • Objective disassembly • Ant colony algorithm

1 Introduction

Nowadays, with the vigorous development of social productivity and science and technology, various mobile phone manufacturers provide people with a rich variety of mobile phone products, which provides great convenience

to people's lives. However, with the replacement of mobile phones and the loss of normal use, there have also been a large number of used mobile phones that cannot be properly disposed of. According to statistics from the Ministry of Industry and Information Technology of China, the stock of used mobile phones in China reached 1.83 billion from 2014 to 2019, while the current recycling rate is less than 1% [1]. Used mobile phones have become an urgent problem to be solved.

Used mobile phones have been considered as a potential source of secondary metals, where the metal content is dozens of times that of natural ore. For example, the gold extraction volume of traditional gold mines is only 1-5 grams per ton, while 250-350 grams per ton can be extracted from used mobile phones [2]. Some parts in used mobile phones have a high residual value and can be recycled or used as parts of secondary products, such as cameras, motherboards, screens, etc. At the same time, used mobile phones also contain harmful substances to human health and the environment, such as cadmium, mercury, and arsenic. Recycling is an effective means to dispose used mobile phones, which can not only recycle the parts or materials to bring economic benefits but also help reduce pollution [3]. In the process of recycling, the first step is to disassemble the mobile phone into parts and recover its usable parts or materials [4]. The disassembly sequence directly affects the time, profit, or energy consumption of disassembly. When manual experience is used to determine the disassembly sequence, it cannot guarantee that the disassembly sequence is optimal, especially when the product has a large number of parts and a complex structure. The purpose of disassembly sequence planning is to find the optimal or suboptimal disassembly sequence under certain sequence evaluation indicators. Disassembly can be divided into complete disassembly and objective disassembly. Complete

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disassembly is to disassemble all parts, while objective disassembly only disassembles specific high-value parts in the product [5]. This paper focuses on objective disassembly as its advantages of short disassembly time and high disassembly profit.

The disassembly schematic diagram is the basis for the research of product disassembly sequence planning. It can describe the basic information of the product parts to be disassembled. The current common disassembly schematic diagrams mainly include AND/OR Graph, Petri nets, directed graphs, and hybrid graph (HG). Previous scholars have done a lot of research based on the above-mentioned disassembly schematic diagrams.

In terms of AND/OR Graph, Lambert [6] uses a binary integer linear programming method to find the disassembly sequence with the lowest disassembly cost. Bentaha et al. [7] proposed an accurate disassembly path planning method for hybrid binary mathematical programming with a joint probability constraint of a lower bound and two upper bounds. However, as the scale of the problem increases, these methods based on mathematical programming inevitably encounter challenges [8]. Ren et al. [9] proposed a priority matrix and exclusion matrix on this basis, established a disassembly model, and used a genetic algorithm to optimize it, which greatly reduced the amount of calculation and calculation time.

In terms of Petri nets, Moore et al. [10] proposed a corresponding disassembly model, taking the number of changes in the disassembly tool and the number of changes in the disassembly direction as the optimization goals, and used a heuristic algorithm to optimize. Guo et al. [11] proposed a method for generating and optimizing objective disassembly sequences under multiple resource constraints. Yang et al. [12] improved the Petri net and proposed an improved Petri net that includes sequence planning, path planning, disassembly tools, disassembly status, and other information.

AND/OR Graph and Petri nets can express all feasible disassembly sequences, but the graphics are too complicated for used mobile phones with many parts and complex structures.

In terms of directed graphs, Han et al. [13] described the priority relationship between parts, took the disassembly time as the optimization goal, and used the branch-defining algorithm for optimization. Ren et al. [14] studied the optimization of energy consumption in the selective disassembly planning. Ren et al. [15] proposed a parallel sequence generation model and used the bee colony algorithm for optimization. Zhang et al. [16] generated the pre-set and subsequent sets of each part and generated

feasible disassembly sequences accordingly. Tseng et al. [17] took the disassembly direction and the conversion times of disassembly tools as the objective function and proposed a new flatworm algorithm for optimization. Deng et al. [18] proposed an asynchronous parallel selective disassembly sequence planning method considering multi-target parts. Liu et al. [19] improved the directed graph. When a part is subject to multiple constraints, the concept of AND and OR is defined for multiple constraints, but the problem of disassembling components is still not solved. Wang and Ren [20] proposed a hierarchical directed graph and a hierarchical constraint matrix.

In terms of HG, Li et al. [21] proposed a disassembly model to simplify the search space, using genetic algorithms for optimization. Li et al. [22] used inference methods to generate feasible disassembly sequences. Wu and Zuo [23] used a genetic algorithm combined with a binary tree algorithm to optimize the objective disassembly sequence. Zhang and Zhang [24] proposed a collaborative disassembly sequence planning method. Zhang et al. [25] proposed a method of selective disassembly sequence planning for a complex product that combines HG and particle swarm algorithms. Tian et al. [26] proposed a theoretical analysis model of disassembly energy. Song et al. [27] proposed a bee colony algorithm for optimization. Wang et al. [28] proposed a selective disassembly sequence planning method considering destructive operations. Zhu et al. [29] proposed a method for product objective disassembly sequence planning and proposed a genetic bat algorithm. Guo et al. [30] established a disassembly model to optimize the disassembly time. Tian et al. [31] proposed a collaborative disassembly sequence planning method. Guo et al. [32] proposed an improved biogeography optimization algorithm, which takes disassembly time and disassembly profit as the optimization objectives to solve the minimum set of necessary parts. Previous scholars have also improved HG. For example, Shi and Wang [33] gave weights to the connection relationship in HG, generated Pareto balanced solution set, and used the ant colony algorithm for optimization. Wei et al. [34] defined destructive disassembly parts and conventional disassembly parts in HG. Jv et al. [35] proposed a disassembly hybrid graph of empowering.

Directed graphs and HG have the advantage of simple graphics, expressing the connection relationship and restraint relationship between parts, and feasible disassembly sequences can be obtained by reasoning. However, the directed graphs and HG can only express the disassembling process one part after another, the

expression of the process of disassembling components is not accurate.

For used mobile phones, one part is often connected to multiple parts at the same time. During the disassembly process, multiple detachable components will be produced. Sometimes disassembling the component may result in a better disassembly sequence. Therefore, the disassembly model must be able to generate a disassembly sequence that includes both parts and components. In this paper, the concepts of containment, exclusion, and components are incorporated into HG, and an improved HG (IHG) is proposed. On the base of IHG, an improved hybrid graph disassembly model (IHGDM) is proposed for used mobile phones disassembly. The IHG retains the advantages of simple graphics. The IHGDM overcomes the drawbacks that the hybrid graph disassembly model (HGDM) cannot represent the process of disassembling components. For the generated feasible disassembly sequence, the disassembly time is taken as the optimization objective, and the ant colony algorithm is used for optimization to find the optimal or suboptimal objective disassembly sequence. Finally, the IHGDM are verified by the example of HUAWEI Honor 6.

2 Improved hybrid graph disassembly model

2.1 Improved hybrid graph

In this paper, the conceptions of the part, component, and disassembly unit will be described. Parts cannot be subdivided by non-destructive disassembly, and a component is a combination of multiple parts that may exist during the disassembly process. The parts and components are collectively referred to as the disassembly unit. The parts can be divided into independent parts and non-independent parts. An independent part can be disassembled through a single disassembly operation. Non-independent parts are those that cannot be disassembled through a single disassembly operation.

The mathematical model of IHG is $G = \{V_d, V_u, V_p, U_d, U_u\}$, where V_d , V_u , V_p are independent parts node, non-independent parts node, and components node respectively; U_d are undirected line segments, representing connection relationships; U_u are directed line segments, representing restraint relationships. To distinguish different types, component nodes are filled with yellow, non-independent part nodes are filled with gray, and independent part nodes have no color. To make the IHG reflect the real part information and disassembly process, only independent parts and components exist in the form of independent nodes in the IHG, and non-independent parts can only be included in

the components. Independent parts can exist either in the form of independent nodes or in the inclusion of components. In this paper, the concept of "family" is defined, that is, parts that belong to the same component are in the same family. IHG only expresses the connection and restraint relationship between independent parts, components, and between parts of the same family. The connection and restraint relationship between the included non-independent part and the disassembly unit outside the same family is expressed by the component to which it belongs.

In the actual disassembly process, a base part is used for fixing or clamping, and other disassembly units are removed from the base part. The base part was also the last to be removed, which is also defined in IHG. The basic ideas of IHG are explained with HUAWEI Honor 6. Figure 1 is the exploded graph of HUAWEI Honor 6 parts (some parts are omitted), and the IHG is shown in Figure 2.

Figure 1 The exploded graph of HUAWEI Honor 6 parts

Figure 2 HUAWEI Honor 6 IHG

As shown in Figure 2, Part 7 is the main body of the mobile phone, Part 7 is defined as a base part. According to the above definition, there are seven parts, namely Part 1,

(3) Containment relationship

The containment relationship is that component contains parts.

Define the containment matrix: containment matrix $C = [c_{ij}]$ is a $N \times N$ square matrix. If Component i contains Part j , then $c_{ij} = 1$, if $i = j$ or Component i do not contain Part j , then $c_{ij} = 0$. Components can only contain parts, not components.

The containment matrix C corresponding to Figure 2 is shown in Table 3.

Table.3 HUAWEI honor 6 containment matrix

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	1	1	0	0	0	0	0	0
9	0	0	0	1	1	0	0	0	0

(4) Exclusion relationship

The exclusion relationship expresses the situation in which one disassembly unit is disassembled and the other disassembly unit does not exist. For example, in Figure 2, if Part 4 is disassembled separately, Component 9 containing Part 4 will naturally not exist, and there will be no disassembly operation of Component 9 in the subsequent disassembly process, so Part 4 excludes Component 9, and vice versa. After Component 9 is removed, Part 4 still exists, and Part 4 may still be disassembled in the subsequent disassembly process. Therefore, Component 9 does not exclude Part 4. When multiple components contain a certain part, these components are mutually exclusive.

Define the exclusion matrix: the exclusion matrix $E = [e_{ij}]$ is a $N \times N$ square matrix. If the disassembly unit i is removed, the Component j does not exist, then $e_{ij} = 1$. If $i = j$ or the disassembly unit i is removed without affecting the Component j , then $e_{ij} = 0$.

The exclusion matrix E corresponding to Figure 2 is shown in Table 4.

Table.4 HUAWEI honor 6 exclusion matrix

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1
3	0	0	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	0	1
5	0	0	0	0	0	0	0	0	1
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0

2.3 Improved hybrid graph disassembly model

The above-mentioned IHG and the link matrix, the restraint matrix, the containment matrix, and the exclusion matrix express the relationship between the disassembly unit, and the IHGDM is formulated according to the above content. Figure 3 shows the IHGDM flow chart. The part labeled in Figure 3 will be described in detail.

① Find the disassembly unit that is not connected

In the set of total disassembly units Ω , find out the disassembly unit corresponding to the sum of row with 0 (the disassembly unit is not connected with any other disassembly unit) and make these disassembly units into a set of detachable disassembly unit Γ .

② Find the unrestrained disassembly unit

If all the disassembly units have connections, find the unrestrained disassembly unit. In the set of total disassembly units Ω , find out the disassembly unit corresponding to the sum of the column of restrain matrix R with 0 (the disassembly unit is not restrained by any other disassembly unit) and make these disassembly units into a set of detachable disassembly unit Γ .

③ Determine the disassembly unit to be disassembled

In set of detachable disassembly units Γ , according to the probability, the Disassembly unit β is selected as the current disassembly unit is detached.

① Generating the set of disassembly Ψ

After confirming the Disassembly unit, the disassembly unit excluded by the Disassembly unit will disappear correspondingly. Therefore, all the disassembly units excluded by are found in the exclusion matrix C ,

which together with the Disassembly unit constitute the set of disassembly Ψ .

② Update link matrix and restraint matrix

In the link matrix L , the rows and column of the corresponding disassembly unit in set Ψ update to 0 (The connection between the disassembly units in set Ψ and

Determine the disassembly unit to be disassembled

Figure 3 IHGDM flow chart

④ Keep the connections and restraints inside the component, and delete the connections and restraints between the component and the outside

If β is a component, find out all disassembly units contained by Component β in the containment matrix C , and make them into the set of part of the same family Π . In the link matrix L , the elements corresponding to the rows of the disassembly units in Π and the columns of the disassembly units outside Π are zeroed; the elements corresponding to the columns of the disassembly units in Π and the rows of the disassembly units outside Π are zeroed (Remove Component β . The connection between the parts that belong to Component β and outside will be disconnected, while the connection inside it will be saved. As shown in Table 5, if Component 9 including Part 4, and Part 5 is disassembled, the gray-filling part of the link matrix will return to zero). In the restraint matrix R , the elements corresponding to the rows of the disassembly units in Π and the columns of the disassembly units outside Π are zeroed (Remove Component β . The restraints that the parts contained in Component β to the outside will be eliminated, while the restraints inside Component β will be saved. As shown in Table 6, if component 9 is

other disassembly units will be disconnected). In the restraint matrix R , the rows of corresponding disassembly units in set Ψ update to 0 (The restraints of the disassembly units in set Ψ to other disassembly units will be eliminated).

disassembled, the gray-filled part of the restraint matrix will return to zero). If β is a part, no change will be made.

⑤ Update the set of total disassembly unit Ω

In the set of total disassembly unit Ω , the disassembly units belong to set Ψ are deleted.

⑥ Judge whether the disassembly sequence contains all target parts

If the disassembly sequence contains all the parts in the set of target parts Φ , the program ends; otherwise, the program returns to the initial part of the process to cycle.

Table.5 Update link matrix

	1	2	3	4	5	6	7	8	9
1	0	1	0	1	0	1	1	1	1
2	1	0	0	0	0	0	0	0	0
3	0	0	0	1	0	0	0	0	1
4	1	0	1	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	1	0	0	0	0	0	0

Table.6 Update restraint matrix

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	1	0	0	1	0	1	1
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	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	0	0	1	1	0	1	0	0	0
9	0	0	1	1	0	1	0	0	0

3 Optimization objective and mathematical model

In the past research, some scholars chose the disassembly time, the number of disassembly direction changes, the number of disassembly tool changes, recycling profits, and disassembly energy consumption as the optimization objective. The number of changes in the direction of disassembly and the number of changes in disassembly tools is ultimately a question of disassembly time. On the issue of disassembly, the disassembly profit is mainly determined by the collection cost of used mobile phones, labor costs, and parts recovery revenue. Among them, the major influence of disassembly profit is labor cost which is mainly determined by disassembly time. There is a greater

correlation between disassembly profit and disassembly time. Therefore, this paper aims to optimize the disassembly time.

In the actual disassembly process of used mobile phones, the disassembly time is mainly divided into disconnection time, tool-conversion time and transfer-time of disassembly unit. The disconnection time is the time that takes to break the connection between the disassembly units. The tool-conversion time is the time consumed by tool conversion. The transfer-time of disassembly unit is the time required in the process of transferring the disassembly unit that has been disassembled to the designated location.

Define the time cellular array Gt which is a $N \times M$ cellular array. Rows N represent the corresponding N disassembly units, and columns M represent the corresponding M parts. The time cellular array is used in units of rows. Each row expresses the connection between the corresponding disassembly unit and other parts, and the time required for disconnection. The elements in the time cellular array are row vectors. $Gt\{i, j\}$ is the element in the i -th row and j -th column of the time cellular array, which expresses the connection between the disassembly unit i and part j . If there is a connection between the disassembly unit i and part j , $Gt\{i, j\}$ is not a zero vector; on the contrary, $Gt\{i, j\}$ is a zero vector. For example, Eq. (1) shows the time cellular array of the HUAWEI Honor 6 in Figure 2.

$$Gt = \begin{bmatrix} [0,0,0,0,0] & [b_1,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] \\ [b_1,0,0,0,0] & [0,0,0,0,0] & [b_2,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [b_3,0,0,0,0] \\ [0,0,0,0,0] & [b_2,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] \\ [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,b_4,0,0] & [0,0,b_5,0,0] & [0,0,0,b_6,0] \\ [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,b_4,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [b_7,0,0,0,0] \\ [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,b_5,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [b_8,0,0,0,0] \\ [0,0,0,0,0] & [b_3,0,0,0,0] & [0,0,0,0,0] & [0,0,0,b_6,0] & [b_7,0,0,0,0] & [b_7,0,0,0,0] & [0,0,0,0,0] \\ [b_1,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [b_3,0,0,0,0] \\ [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,0,0,0] & [0,0,b_5,0,0] & [b_7,0,0,b_6,0] \end{bmatrix} \quad (1)$$

In Figure 2, there are 9 disassembly units and 7 parts, so the time cellular array has 9 rows and 7 columns. There are 5 connection methods, namely glued connection, screw connection, BTB connection, snap connection, and embedded connection, so there are 5 elements in each row vector. There is only a glued connection between Part 1 and Part 2, suppose the time required to disconnect is b_1 , then $Gt\{1,2\} = [b_1,0,0,0,0]$. Figure 4 is $Gt\{1,2\}$ expressing information schematic diagram.

Figure 4 Time cell array element expression information schematic diagram

Define the tool vector Tool. The tool vector is a row vector with the number of elements equal to the number of tool types. Each element represents whether the corresponding tool is used. If a tool is used, the corresponding element is 1, otherwise, it is 0. When the

sum of all the elements in the row of a certain disassembly unit in the time cellular array Gt is determined, the tool vector for disassembling this disassembly unit can be determined. The tools needed to disconnect the glued connection are the heating plate and the suction cup; the tools needed to disconnect the screw connection are electric screwdrivers; the tools needed to disconnect the BTB connection are tweezers; the tool needed to disconnect the snap connection is a crowbar; the tool needed to disconnect the embedded connection are tweezers. In figure 1, when disassembling Part 1, it is necessary to disconnect a glued connection, then its corresponding tool vector is. The schematic diagram of the correspondence between connection and tool vector is shown in Figure 5.

Figure 5 Schematic diagram of the correspondence between connection and tool vector

The time to disconnect a certain connection, the time of a single tool conversion, and the time of a single transfer disassembly unit are the average values of multiple actual disassembly measurements. The calculation steps of disassembly time and the corresponding mathematical model are shown in Table 7.

Table 7 Calculation steps of disassembly time and corresponding mathematical model

step	operation	mathematical model
1	Initial data	$\alpha = 1; T_l = 0; T_s = 0; T_m = 0; T_z = 0$
2	The disconnection time, tool- conversion time, and transfer-time of disassembly unit of S_α are calculated	$T_l = \text{sum}(\sum_{j=1}^M Gt\{S_\alpha, j\}); \text{Tool} = f(\sum_{j=1}^M Gt\{S_\alpha, j\});$ $T_s = \text{sum}(\text{Tool}) \cdot c; T_m = n \cdot d$
3	Delete the connection of S_α with other disassembly units in Gt	$Gt\{S_\alpha, j\} = [0, 0, L, 0], j = 1, 2, L, M$ $Gt\{j, S_\alpha\} = [0, 0, L, 0], j = 1, 2, L, N$
4	Judge whether S_α is a part, if yes, turn 5, otherwise turn 6	--
5	Delete the connection between the disassembly unit contained by S_α and the outside in Gt	$Gt\{j, k\} = [0, 0, L, 0], c_{S_\alpha, j} = 1, c_{S_\alpha, k} = 0 \text{ 且 } k = 1, 2, L, M$ $Gt\{k, j\} = [0, 0, L, 0], c_{S_\alpha, j} = 1 \text{ 且 } j = 1, 2, L, M, c_{S_\alpha, k} = 0$
6	Whether $\alpha = n$, if yes, it ends; otherwise, $\alpha = \alpha + 1$, it turns to 2	$T_z = T_z + T_l + T_s$

Among them, T_l is the disconnection time; T_s is the tool- conversion time; T_m is the transfer- time of disassembly unit; T_z is the total disassembly time; S_α is the α -th disassembly unit in the disassembly sequence; sum is an operator, that is, sum all the elements in the vector; f is an operator, that is, the corresponding relationship between the connection and the application tool; c is the time required for a single conversion tool; d is the time required for a single transfer disassembly unit; n is the total number of disassembly unit in the disassembly sequence.

4 Disassembly sequence optimization

As the number of product parts increases, the number of feasible disassembly sequences will increase exponentially. There are a large number of parts in mobile phone, and there are tens of thousands of feasible disassembly sequences. If combined and optimized manually, the process would be very cumbersome and difficult to achieve. Therefore, intelligent algorithms are used to optimize the

sequence. The current intelligent algorithms used in disassembly sequence optimization mainly include ant colony algorithm [36-38], genetic algorithm [39-42], bee colony algorithm [43-45], particle swarm algorithm [46]. For objective disassembly, the lengths of the disassembly sequence are different. The ant colony algorithm is more tolerant to this feature, so the ant colony algorithm is selected for optimization. The flowchart of the ant colony algorithm is shown in Figure 6.

Figure 6 The flowchart of ant colony algorithm

When the ant colony algorithm is applied to the disassembly sequence optimization, multiple generations of optimization will be performed. Each ant is equivalent to an individual. Each disassembly sequence is equivalent to a path traversed by an ant. Each generation produces a population. A population contains multiple individuals.

(1) Pheromone matrix

The pheromone matrix $Tau = \tau_{jk}$ is a $(N+1) \times N$ matrix. According to the function of the pheromone matrix, a virtual disassembly unit 0 is defined to determine the probability of the first disassembly unit in the disassembly sequence. The first row of the pheromone matrix represents the virtual disassembly unit 0, and the following rows N represent N actual disassembly unit in turn. τ_{1j} determines the probability of disassembly unit j as the first disassembly unit to be disassembled. The larger the value of τ_{1j} , the greater the probability that disassembly unit j will be selected; $\tau_{k+1,j}$ ($k=1,2,L,N$) determines the probability of the disassembly unit j as the next disassembly unit after the disassembly unit k is disassembled. Initially, each element of the pheromone matrix is assigned an initial value.

(2) Generating sequence

When selecting the disassembly unit from the set of detachable disassembly unit Γ , the probability of each disassembly unit being selected is calculated according to the value of the pheromone matrix. The roulette method is used to determine the disassembled unit.

When the first disassembly unit of a disassembly sequence is determined, the probability of disassembly unit j being disassembled P_j is calculated by Eq.(2).

$$P_j = \frac{\tau_{1j}}{\sum_{i=1}^N \tau_{1i}} \quad (2)$$

When determining the non-first disassembly unit of a disassembly sequence, suppose disassembly unit k is the last disassembled, then the probability of disassembly unit j being disassembled P_j is calculated by Eq.(3).

$$P_j = \frac{\tau_{k+1,j}}{\sum_{i=1}^N \tau_{k+1,i}} \quad (3)$$

(3) Fitness value

The fitness of the disassembly sequence is the only criterion to measure the pros and cons of an individual, and it is also the key to the implementation of the optimization algorithm. Generally, the fitness of an optimization algorithm is related to the optimization objective. In this paper, the optimization goal is the disassembly time, which is directly used as the fitness.

(4) Update pheromone matrix

In the ant colony algorithm of this paper, only the best individual in each generation is used to update the pheromone matrix. The specific update functions are as follows:

Update line 1 of pheromone matrix:

$$\tau_{0,S_\alpha}(t+1) = (1-\rho) \cdot \tau_{0,S_\alpha}(t) + \Delta\tau, \alpha = 1$$

Update pheromone matrix lines 2 to $N+1$:

$$\tau_{S_{\alpha-1}+1,S_\alpha}(t+1) = (1-\rho) \cdot \tau_{S_{\alpha-1}+1,S_\alpha}(t) + \Delta\tau, \alpha = 2,3,L,n$$

Among them, $\tau(t)$ is the value of the t -th generation pheromone matrix; ρ is the pheromone volatilization coefficient; $\Delta\tau$ is the pheromone increment.

5 Experiential verification

5.1 HUAWEI Honor 6 part information

In this section, HUAWEI Honor 6 as an example is taken to verify the IHGDM. As shown in Figure 7, HUAWEI Honor 6 has 12 parts, including back cover 1, cover plate 2, loudspeaker 3, battery 4, switch 5, motor 6, rear camera 7, motherboard 8, front camera 9, screen 10, receiver 11, and main body 12. Among them, there are 8 independent parts, including back cover 1, battery 4, switch 5, motor 6, rear camera 7, screen 10, receiver 11, and main body 12, while there are 4 non-independent parts, including cover plate 2, loudspeaker 3, motherboard 8 and front camera 9.

In HUAWEI Honor 6, there are 17 possible components. The corresponding relationship between the components and the parts is shown in Table 8. The corresponding HUAWEI honor 6 IHG is shown in Figure 8.

Figure 7 HUAWEI honor 6 parts graph

There are 5 connection methods for HUAWEI Honor 6 mobile, namely, glued connection, screw connection, BTB connection, snap connection, and embedded connection. Each element in the time cell array is a row vector of. All the time data in the time cell array are the average of 3 actual disassembly experiments. According to the experiment, the time required for a single tool conversion

is 2.6 seconds, and the time required for a single disassembly unit transfer is 1.9 seconds. The

corresponding relationship between HUAWEI Honor 6 connections and tools is shown in Figure 5.

Table.8 The corresponding relationship between the components and the parts

The serial number of the component	The parts contained in the component
13	cover plate and loudspeaker
14	motherboard, front camera, rear camera, motor, switch and battery
15	motherboard, front camera, rear camera, motor and switch
16	motherboard, front camera, rear camera, motor and battery
17	motherboard, front camera, rear camera, switch and battery
18	motherboard, front camera, motor, switch and battery
19	motherboard, front camera, rear camera and motor
20	motherboard, front camera, rear camera and switch
21	motherboard, front camera, rear camera and battery
22	motherboard, front camera, motor and switch
23	motherboard, front camera, motor and battery
24	motherboard, front camera, switch and battery
25	motherboard, front camera and rear camera
26	motherboard, front camera and motor
27	motherboard, front camera and switch
28	motherboard, front camera and battery
29	motherboard and front camera

Figure 8 HUAWEI Honor 6 IHG

The IHGDM program and the HGDM program were written using MATLAB. The corresponding serial number of the part in the HGDM program is the same as the corresponding serial number of the part in the IHGDM program, but there is no component. In the case of the same data, the simulation process changes the target part and compares HGDM with IHGDM. In the ant colony algorithm, the population size of each generation is 20, and 300 generations are optimized.

5.2 Results and discussion

5.2.1 Convergence rate and optimization results

According to market research, the parts with high recycling value in HUAWEI Honor 6 are the motherboard, camera, and screen. Generally, the front camera and the rear camera are usually recycled together, they are combined into one part in this paper. The parts with high recycling value are selected as the target parts. The results of single-target disassembly, multi-target disassembly, and

complete disassembly optimization are shown in Figure 9

and Table 9.

Figure 9 Comparison of optimization results of different target parts

Table 9 Comparison of results of different target parts

Label	Target part	Disassembly model	Disassembly sequence	Disassembly time (s/second)	Optimization degree
(a)	motherboard + camera+ screen	IHGDM	1-13-28-7-10-8-9	173.73	8.44%
		HGDM	1-2-3-8-4-10-7-9	189.76	
(b)	camera+ screen	IHGDM	1-13-28-7-10-9	166.74	12.66%
		HGDM	1-2-3-8-4-10-9	187.86	
(c)	motherboard + screen	IHGDM	1-13-21-8-10	169.93	8.62%
		HGDM	1-2-3-8-4-10	185.96	
(d)	motherboard + camera	IHGDM	1-13-29-7-8-9	129.75	9.82%
		HGDM	1-2-3-8-7-9	143.88	
(e)	screen	IHGDM	1-13-4-10	146.28	13.91%
		HGDM	1-2-3-4-10	169.93	
(f)	camera	IHGDM	1-13-29-7-9	127.85	11.14%
		HGDM	1-2-3-8-9-7	143.88	
(g)	motherboard	IHGDM	1-13-29-7-8	125.95	10.87%
		HGDM	1-2-3-8	140.08	
(h)	complete disassembly	IHGDM	1-13-18-7-2-3-10-11-12-8-9-6-5-4	225.69	0.79%
		HGDM	1-2-3-8-7-4-10-5-6-9-11-12	227.49	

In Figure 9, the optimal disassembly time curve is the disassembly time curve of the best individual among the 20 individuals in the per generation; the average disassembly time curve is the average disassembly time curve of the 20 individuals in the per generation. It can be seen that the convergence speed of HGDM is faster than IHGDM in both the optimal disassembly time curve and the average disassembly time curve. However, the final optimization result obtained by IHGDM is better than HGDM. This is because IHG has added all possible disassembly components based on HG. IHGDM includes HGDM in the space of feasible disassembly sequences, so IHGDM is slower in convergence speed, but can generate better disassembly sequences. It can be seen from Table 9 that in the case of objective disassembly, the disassembly time of IHGDM is reduced by 8.44%-13.91% compared with HGDM. Among them, the optimization of the screen as the target part is the most obvious, reaching 13.91 %; the degree of optimization is the lowest with the motherboard, camera, and screen as the target parts, which is 8.44%.

When all parts in a component are not target parts, but multiple parts constitute constraints on the target part, HGDM can only disassemble the constrained target part after disassembling the parts in the component separately. In IHGDM, the target part can be disassembled after the whole component is disassembled directly. In this case, IHGDM can save the time required to disconnect the internal parts of the component, and then get a better disassembly sequence.

5.2.2 Disassembly sequence and actual disassembly process

The case where the motherboard is the target part in Table 9 shows that the disassembly sequence (1-2-3-8) generated by HGDM does not completely disassemble the motherboard. The motherboard at this time is connected to the front camera (the motherboard is connected to the front camera and also constrains the front camera), which is a component. Therefore, HGDM does not accurately express the actual disassembly process. However, IHGDM expresses this process well, and the disassembly sequence it generates is 1-13-29-7-8. After disassembling Component 29 (including the motherboard and the front camera), the motherboard is disassembled from Component 29. The motherboard at this time is a part. Compared with HGDM, the disassembly sequence generated by IHGDM can reflect the actual disassembly process more accurately.

5.2.3 Disassembly time analysis

Figure 10 shows the disconnection time, tool-conversion time, and transfer-time of disassembly unit in the case of different target parts, as well as the reduction of each partial time relative to HGDM.

The transfer-time of disassembly unit reflects the number of disassembly units in the disassembly sequence. When the target part is the motherboard and complete disassembly, the transfer-time of disassembly unit of IHGDM is higher than that of HGDM. Although IHGDM can shorten the disassembly sequence by disassembling components

(equivalent to disassemble multiple parts at a time), it adds the steps of disassembling components. Therefore, IHGDM may be more than HGDM in transfer-time of disassembly unit.

Figure 10 Partial disassembly time

Compared with HGDM, the reduction in tool-conversion time of IHGDM is mainly due to the addition of components. There are more options when choosing the next disassembly unit to be dismantled. Therefore, the disassembly sequence can be further optimized and the number of conversion tool can be reduced.

IHGDM has the most obvious optimization in disconnection time. This also shows that IHGDM reduces the time required to disconnect to the internal connections of the components mainly by disassembling the components. But in the case of complete disassembly, the disconnection time of IHGDM is optimized to 0. This is because regardless of the disassembly model, the connections to be disconnected when all parts need to be disassembled are the same.

5.2.4 The number of target parts and optimization degree

In Table 9, there are three cases where the target parts quantity is 1 and 2, and the average optimization is calculated respectively; there is only one case where the target parts quantity is 3, namely case (a); there is one case where the target parts quantity is 11, namely case (h). The calculation result is shown in Figure 11.

As the number of target parts increases, IHGDM has a decreasing trend in the optimization of disassembly time compared with HGDM. This is because the optimization of IHGDM is mainly to save the time of disconnecting the internal connection of the component. When there are fewer target parts, the possibility of disassembling components into parts will be reduced, and the components will be disassembled as completely as possible. Conversely,

when there are many target parts, it will increase the possibility of splitting the components into parts, thereby reducing the advantages of IHGDM. Therefore, IHGDM is more suitable for the objective disassembly with fewer target parts. For the complete disassembly of IHGDM, only 0.79% is optimized, and the advantage is not obvious.

Figure 11 Average optimization degree of different number of target parts

6 Conclusions

In this paper, based on the characteristics that mobile phone parts are connected to multiple parts at the same time and the disassembly of the components often occurs during the process of disassembling the mobile phone, the concept of containment, exclusion, and components are integrated into HG, and this paper proposes a suitable IHGDM based on IHG. The mathematical model of the cellular array is used to express the disassembly time of parts. The ant colony algorithm is used to search for the optimal disassembly sequence, with the objectives of minimum disassembly time. Finally, the HUAWEI Honor 6 was used as an example to verify the IHGDM.

(1) IHGDM can generate a disassembly sequence containing components. In the case of objective disassembly, the disassembly time of IHGDM is reduced by 8.44%-13.91% compared with HGDM. Among them, the optimization of the screen as the target part is the most obvious, reaching 13.91%; with the motherboard, camera, the screen is the least optimized for the target part, which is 8.44%.

(2) The disassembly sequence generated by IHGDM expresses the actual disassembly process accurately.

(3) IHGDM mainly reduces disconnection time and tool-conversion time compared with HGDM. In the case of

complete disassembly, the two disassembly models are the same in disconnection time.

(4) As the number of target parts increases, IHGDM has a decreasing trend in the optimization of disassembly time compared with HGDM. IHGDM is more suitable for the disassembly of target parts with a small number of target parts.

In the face of the current huge stock of used mobile phones and the rising trend of the volume, the IHGDM proposed in this paper can better solve the problem of objective disassembly sequence planning for used mobile phones. The IHGDM can also be applied to other products similar to mobile phones, which have a wider scope of application than HGDM.

IHGDM can realize the function of disassembling components mainly by adding components that may exist in the disassembling process in IHG in advance. However, when the structure of the product is too complex, finding out all possible components is a huge workload. At the same time, when disassembling the component, a parallel disassembly line can be added to realize parallel disassembly. Therefore, future work could include the following: a. improve the disassembly model. Through the connection relationship and restraint relationship between the parts, the disassembled components are directly generated; b. parallel disassembly is realized on the base of disassembling components.

7 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

Fengfu Yin Conceptualization, Methodology, Writing-Original draft preparation. Xiaodong Wang Data curation, Writing- Original draft preparation. Hongrui Li Software, Conceptualization, Investigation. Huadong Sun Conceptualization, Investigation. Suiran Yu Experiment Design. Writing - Review & Editing; Lin Li Validation, Writing - Review & Editing, Funding acquisition. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing financial interests.

Consent for publication

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Table A.5 HUAWEI Honor 6time cellular array

	1	2	3	4	5	6	7	8	9	10	11	12
1	Gt_0	Gt_1	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0
2	Gt_1	Gt_0	Gt_2	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0
3	Gt_0	Gt_2	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0
4	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_3	Gt_0	Gt_0	Gt_0	Gt_4
5	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_5	Gt_0	Gt_0	Gt_0	Gt_6
6	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_7	Gt_0	Gt_0	Gt_0	Gt_8
7	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_9	Gt_0	Gt_0	Gt_0	Gt_0
8	Gt_0	Gt_0	Gt_0	Gt_3	Gt_5	Gt_7	Gt_9	Gt_0	Gt_{10}	Gt_{11}	Gt_0	Gt_0
9	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{10}	Gt_0	Gt_0	Gt_0	Gt_0
10	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_0	Gt_0	Gt_{12}
11	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{13}
12	Gt_0	Gt_0	Gt_0	Gt_4	Gt_6	Gt_8	Gt_0	Gt_0	Gt_0	Gt_{12}	Gt_{13}	Gt_0
13	Gt_1	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{14}
14	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{15}
15	Gt_0	Gt_0	Gt_0	Gt_3	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{16}
16	Gt_0	Gt_0	Gt_0	Gt_0	Gt_5	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{17}
17	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_7	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{18}
18	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{19}
19	Gt_0	Gt_0	Gt_0	Gt_3	Gt_5	Gt_0	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{20}
20	Gt_0	Gt_0	Gt_0	Gt_3	Gt_0	Gt_7	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{21}
21	Gt_0	Gt_0	Gt_0	Gt_0	Gt_5	Gt_7	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{22}
22	Gt_0	Gt_0	Gt_0	Gt_3	Gt_0	Gt_0	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{23}
23	Gt_0	Gt_0	Gt_0	Gt_0	Gt_5	Gt_0	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{24}
24	Gt_0	Gt_0	Gt_0	Gt_0	Gt_0	Gt_7	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{25}
25	Gt_0	Gt_0	Gt_0	Gt_3	Gt_5	Gt_7	Gt_0	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{26}
26	Gt_0	Gt_0	Gt_0	Gt_3	Gt_5	Gt_0	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{27}
27	Gt_0	Gt_0	Gt_0	Gt_3	Gt_0	Gt_7	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{28}
28	Gt_0	Gt_0	Gt_0	Gt_0	Gt_5	Gt_7	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{29}
29	Gt_0	Gt_0	Gt_0	Gt_3	Gt_5	Gt_7	Gt_9	Gt_0	Gt_0	Gt_{11}	Gt_0	Gt_{30}

$$Gt_0 = [0, 0, 0, 0, 0], Gt_1 = [15.42, 0, 0, 0, 0], Gt_2 = [0, 0, 0, 0, 3.19], Gt_3 = [0, 0, 5.09, 0, 0], Gt_4 = [15.88, 0, 0, 0, 0], Gt_5 = [0, 0, 3.11, 0, 0],$$

$$Gt_6 = [0, 0, 0, 4.58, 0], Gt_7 = [0, 0, 1.63, 0, 0], Gt_8 = [11.92, 0, 0, 0, 0], Gt_9 = [0, 0, 3.42, 0, 0], Gt_{10} = [0, 0, 2.05, 0, 0],$$

$$Gt_{11} = [0, 0, 2.02, 0, 0], Gt_{12} = [15, 0, 0, 0, 0], Gt_{13} = [0, 0, 0, 0, 2.43], Gt_{14} = [0, 64.44, 0, 9.65, 0], Gt_{15} = [27.8, 0, 0, 8.68, 0],$$

$$Gt_{16} = [11.92, 0, 0, 8.68, 0], Gt_{17} = [27.8, 0, 0, 4.1, 0], Gt_{18} = [15.88, 0, 0, 8.68, 0], Gt_{19} = [27.8, 0, 0, 8.68, 0], Gt_{20} = [11.92, 0, 0, 4.1, 0],$$

$$Gt_{21} = [0, 0, 0, 8.68, 0], Gt_{22} = [15.88, 0, 0, 4.1, 0], Gt_{23} = [11.92, 0, 0, 8.68, 0], Gt_{24} = [27.8, 0, 0, 4.1, 0], Gt_{25} = [15.88, 0, 0, 8.68, 0],$$

$$Gt_{26} = [0, 0, 0, 4.1, 0], Gt_{27} = [11.92, 0, 0, 4.1, 0], Gt_{28} = [0, 0, 0, 8.68, 0], Gt_{29} = [15.88, 0, 0, 4.1, 0], Gt_{30} = [0, 0, 0, 4.1, 0].$$