Life Cycle Management of LCD Televisions – Case Study

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Guoqing Jin and Weidong Li

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Abstract

Waste Electrical and Electronic Equipment (WEEE) is one of the most significant waste products in modern societies. Disassembly is a critical step to reduce Electrical and Electronic Equipment (EEE) waste. In the past two decades, despite disassembly has been applied to support recycling and remanufacturing of WEEE products worldwide, full disassembly of WEEE is rarely an ideal solution due to high disassembly cost. Selective disassembly, which prioritizes operations for partial disassembly according to the economic considerations, is becoming an important but still a challenging research topic in recent years. In order to address the issue effectively, in this chapter, space interference matrix is generated based on a product model to represent the space interference relationship between each component, and all feasible disassembly sequences can be obtained by analyzing the space interference matrix with a matrix analysis

G. Jin (✉) • W. Li
Faculty of Engineering and Computing, University of Coventry, Coventry, UK
e-mail: guoqing.jin@coventry.ac.uk; weidong.li@coventry.ac.uk

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algorithm. Then, a particle swarm optimization (PSO)-based selective disassembly planning method embedded with customizable decision-making models is applied, which is capable to achieve optimized selective disassembly sequences for products. Finally, industrial cases on liquid crystal display (LCD) televisions are used to verify and demonstrate the effectiveness and robustness of the developed research.

Introduction

The mounting demand for new products has brought more production activities worldwide in recent years. The rapid development, however, has been hindered by the increasing concerns of the scarcity of natural resources and environmental issues. It has been estimated that the required bio-capacity of two Earths is necessary to satisfy the need of the development in 2050 according to current production and consumption trends (Jovane et al. 2008). On the other hand, more and more products after services are filled up in landfills. Among them, Electrical and Electronic Equipment (EEE) after services, that is, Waste Electrical and Electronic Equipment (WEEE), is becoming one of the major and challenging waste streams in terms of quantity and toxicity. For instance, there is approximately seven million tons of WEEE generated in Europe per year (Walther et al. 2010). In China, 1.1 million tons of WEEE is generated per year (Hicks et al. 2005). Due to the rapid technical innovations and shorter usage life cycle of EEE, WEEE is growing much faster than any other municipal waste streams. In order for the Earth to be cleaner, end-of-life (EoL) recovery strategies are critical to shape the future of WEEE life cycle management patterns. Among the strategies, remanufacturing is viewed as a “hidden green giant” and attracting escalating attentions of researchers and practitioners (Kopacek and Kopacek 1999; Duflou et al. 2008; Kernbaum et al. 2009; Hatcher et al. 2011). Remanufacturers seek to bring some components of products after their services back into “as new” conditions by carrying out necessary disassembly, overhaul, and/or repairing operations for reuse to extend life cycles. There are two driving forces for industries in adopting the relevant technologies and practices, i.e., stricter legislative pressure for environmental protection and better profit margins from remanufacturing. The explanations are expanded below:

- The WEEE Directive has been enacted and implemented from 2003 in Europe, and the equivalent Directives have been developed in different countries of the world. Further proposals for the tighter WEEE Directives have been suggested to regulatory bodies with an aim to make products and components after services more recyclable, reusable, and remanufacturable. According to the WEEE Directives, a producer (manufacturer, brand owner, or importer)’s responsibility is extended to the postconsumer stage of WEEE, instead of stopping at selling and maintenance (i.e., extended producer responsibility – EPR; Mayers 2007;

Sander et al. 2007). The EPR is aimed at encouraging producers especially manufacturers to provide cradle-to-grave support to reduce environmental impacts such that they work closely with remanufacturing industries to recover maximum values and reduce environmental toxicity/hazardousness. For instance, the remanufacturing legislative initiatives are underway in the EU and the USA to ensure original equipment manufacturers (OEMs) and suppliers to provide free access to remanufacturing information facilities in global chains (Giuntini and Gaudette 2003).

- Good remanufacturing planning and management can effectively balance economic and environmental targets and close gaps between the shorter innovation cycles of EEE and the extended lives of components of WEEE. Remanufacturing industries in the EU and worldwide have been recently growing quickly because of better economic return values. There are a number of successful cases in industries, including single-use cameras (Eastman Kodak and Fujifilm), toner cartridges (Xerox), personal computers (IBM, HP, Toshiba, Reuse network – Germany), photocopiers (Fuji Xerox – Australia, Netherlands, and UK), commercial cleaning equipment (Electrolux), washing machines (ENVIE – France), mobile phones (Nokia, ReCellular, USA; Greener Solution, UK), etc.

Disassembly planning, which is used to determine sensible disassembly operations and sequencing, is critical in remanufacturing. Effective disassembly planning can significantly improve the recycling and reuse rates of components and materials from WEEE to ensure maximum value recovery. For a set of WEEE, there could be a number of different sequences of disassembly operations constrained technically and geometrically between the components of the WEEE, leading to the different decision-making models according to the perspectives and criteria of stakeholders (Kara et al. 2006). As thus, it becomes difficult for remanufacturers to solely depend upon their experiences to plan disassembly operations so as to recover a larger proportion of components and fulfill environmental targets at a reasonable cost. In the past years, research has been carried out to address the issues of disassembly. The previous research can be generally summarized as the following two categories:

- Disassembly for design. Disassembly approaches for EEE such as consumer electronic products have been developed to use smart materials like shape memory polymers (SMPs) in the design of embedded releasable fasteners to facilitate the disassembly processes of the products (Masui et al. 1999; Chiodo et al. 2001; Jones et al. 2004; Braunschweig 2004; Hussein and Harrison 2008; Ijomah and Chiodo 2010). Design for remanufacturing/disassembly principles have been spread among Japanese manufacturers since products with the principles are more profitable in this context than those that were not designed with this purpose (Duflou et al. 2008; Sundin et al. 2009; Dindarian et al. 2012).
- Disassembly planning and operation sequencing. Typical disassembly operations based on manual, semiautomatic, and automatic processes and the

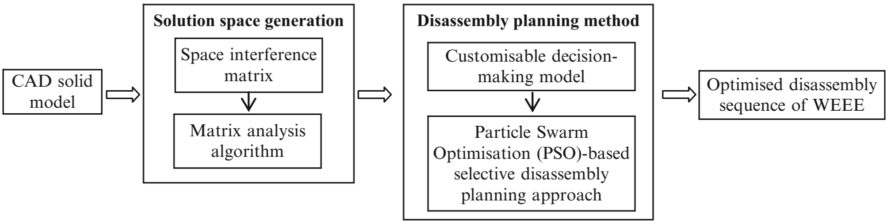

Fig. 1 A main flow of the developed approach

associated toolkits were summarized (Duflou et al. 2008). Based on disassembly operations and the precedence constraint relationships among the disassembly operations, sequencing rules and intelligent and/or meta-heuristic reasoning algorithms were applied to deduce an optimal plan from a large pool of candidate solutions (Kara et al. 2006; Santochi et al. 2002; Lambert 2002; Kuo 2012). In recent years, remanufacturers are facing many challenges to disassemble WEEE due to their high customization and diversity, high integration level, and more complex assembly processes. Current economic analyses have demonstrated that full disassembly is rarely an optimal solution and necessary owing to high disassembly cost. Selective disassembly, which prioritizes operations to implement partial dismantling of WEEE so as to take account of the legislative and economic considerations and meet the specific requirements of stakeholders, is a promising alternative and has therefore become a new research trend (Duflou et al. 2008; Renteria et al. 2011; Ryan et al. 2011).

Attributing to booming personalized and mass-customized EEE, there is still challenge in applying the developed methods to the increasingly diversified and personalized WEEE to make sensible decisions and meet different stakeholders' perspectives. This chapter presents a new method conducted in the area, and the main flow of the method is shown in Fig. 1. A summary of the developed approach is given below:

- A space interference matrix is used to represent the space relationship of each component of WEEE in six directions in a Cartesian coordinate system. By this way, all the space interference relationships between components of WEEE can be digitally recorded and can be analyzed in the next step.
- A matrix analysis algorithm is developed to find out all the feasible disassembly sequences of WEEE by analyzing the six space interference matrices in a 3D environment. It is capable to find out all the feasible disassembly sequences of WEEE, and the result can be used as a solution space to support a disassembly planning method to search optimized result.
- A particle swarm optimization (PSO)-based selective disassembly planning method with customizable decision-making models has been

developed. The method is adaptive to various types of WEEE, flexible for customized decision modeling and decision making for different stakeholders, and capable for handling complex constraints and achieving better economic value and environmental protection requirements during disassembly planning.

- In the end, industrial case studies on liquid crystal display (LCD) televisions are used to verify and demonstrate the effectiveness of the developed method in different application scenarios.

Methodology

Space Interference Matrix and Matrix Analysis Algorithm

In the past two decades, there are many research articles published for disassembly research of WEEE. In the literature (Ying et al. 2000; Lambert 2003; Carrell et al. 2009), some detailed reviews on the research were made. Almost all those researches focused on the optimal disassembly solution searching. However, before applying disassembly planning and optimization techniques in real industrial cases such as LCD televisions, which is one of the main products of WEEE nowadays, it cannot evade the issue of the feasible solution space generation for further search and optimization (Wang et al. 2014). There are two reasons: (1) in real practice, if the disassembly sequence is obtained by searching all the disassembly sequences instead of the solution space, the result could hardly be used as there are some geometrical constraints to specify precedent relationships between disassembly operations, and (2) LCD televisions are normally assembled by many components with complex shapes. For an assembly LCD television with N components, the total disassembly sequences could be as much as $N! = N \times (N-1)...2 \times 1$. It is too difficult to search the best disassembly sequence within an acceptable runtime. In this section, an effective approach was developed to address the issues of the solution space generation of WEEE.

Space Interference Matrix

Firstly, based on a CAD product model, six space interference matrices are generated in six directions separately in a 3D environment. It can be used to represent the space interference relationship of components of a product:

$$\begin{array}{c} \\ E_1 \\ E_2 \\ \vdots \\ E_n \end{array} \begin{array}{c} \begin{array}{cccc} E_1 & E_2 & \cdots & E_n \end{array} \\ \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & & \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & & t_{nn} \end{bmatrix} \end{array} \tag{1}$$

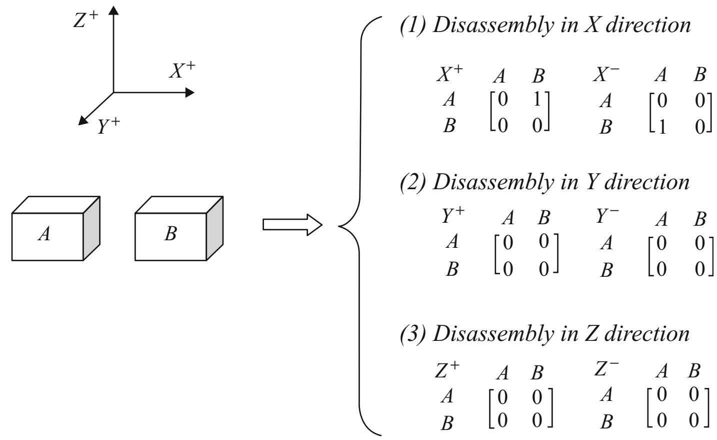

Fig. 2 Matrices in six directions to represent the space interference relationship

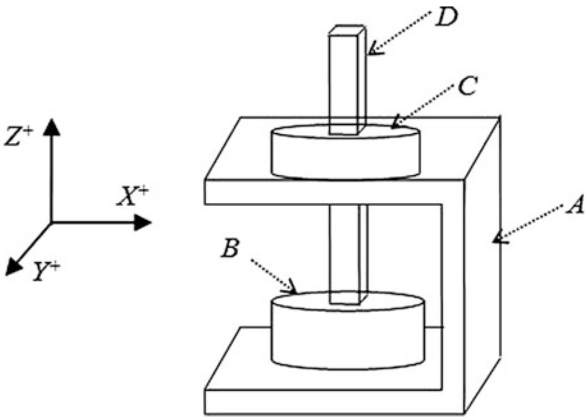

Fig. 3 Product with four components

In the matrix, the element E_i in each row and column is one of the components in the product. The element t_{ij} shows the space interference relationship between components i and j in six directions (X^+, X^-, Y^+, Y^-, Z^+, Z^-) in a 3D environment. If space interference exists between components i and j in one direction, the element t_{ij} in the matrix is "*1*" in this direction. Otherwise, it is "*0*."

An example is used here to explain the space interference relationship between "*A*" and "*B*" (shown in Fig. 2). As the object "*B*" is in the X^+ direction of the object "*A*," and the object "*A*" is in the X^- direction of the object "*B*," the element t_{AB} in the X^+ direction matrix is "*1*," and the element t_{BA} in the X^- direction matrix is "*1*," all other results are "*0*."

For example, Eqs. 2, 3, 4, 5, 6, and 7 are used to represent the space interference relationship between four components of a product (shown in Fig. 3):

$$S_{X^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \tag{2}$$

$$S_{X^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \tag{3}$$

$$S_{Y^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \tag{4}$$

$$S_{Y^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \tag{5}$$

$$S_{Z^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \tag{6}$$

$$S_{Z^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \tag{7}$$

Matrix Analysis Algorithm

Based on the obtained space interference matrices in six directions in above, a matrix analysis algorithm is then developed to find all the feasible disassembly sequences of the product. Figure 4 shows the flow of the algorithm.

An example is used here to explain the details of the developed matrix analysis algorithm. Firstly, Eq. 8 is generated by combining Eqs. 2, 3, 4, 5, 6, and 7 in six directions:

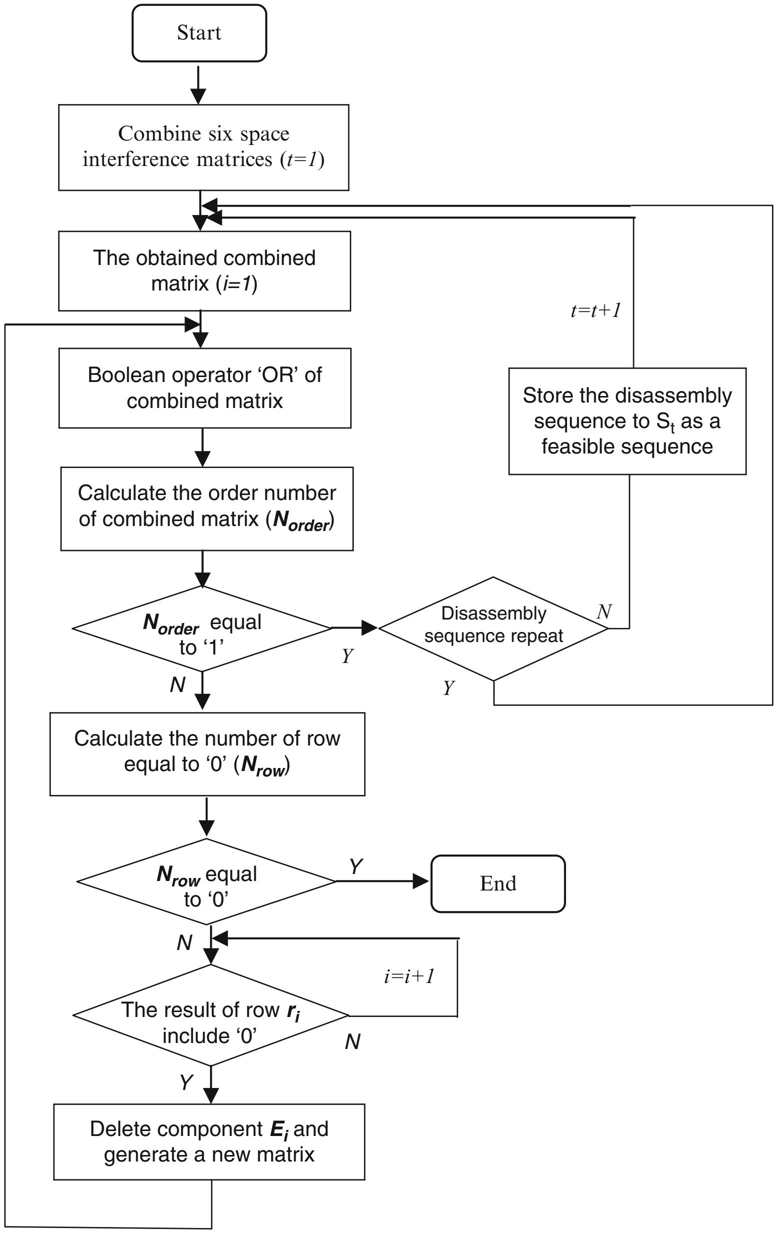

Fig. 4 Flowchart of the matrix analysis algorithm

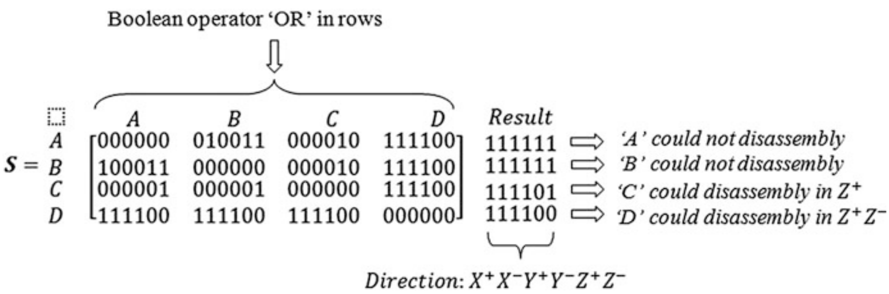

Fig. 5 Feasible disassembly sequence analysis for the product

$$\boldsymbol{S} = \begin{matrix} & A & B & C & D \\ A & 000000 & 010011 & 000010 & 111100 \\ B & 100011 & 000000 & 000010 & 111100 \\ C & 000001 & 000001 & 000000 & 111100 \\ D & 111100 & 111100 & 111100 & 000000 \end{matrix} \tag{8}$$

The Boolean operator "OR" is used here for the above equation at any row to determine whether a component can be freely disassembled in a direction. Equation 9 is obtained below:

$$\boldsymbol{S} = \begin{matrix} & A & B & C & D & \text{Result} \\ A & 000000 & 010011 & 000010 & 111100 & 111111 \\ B & 100011 & 000000 & 000010 & 111100 & 111111 \\ C & 000001 & 000001 & 000000 & 111100 & 111101 \\ D & 111100 & 111100 & 111100 & 000000 & 111100 \end{matrix} \tag{9}$$

The result "111111" represents the relationship between one component and all remaining components of the product in six directions (X^+, X^-, Y^+, Y^-, Z^+, Z^-). If the result is always "1," it means the component could not be disassembled in any direction; if the result includes "0," it means the component can be disassembled from that direction. The example in Fig. 5 can be used to explain the concept. In Eq. 2, components "*A*" and "*B*" could not be disassembled in any direction as the result is all "1"; component "*C*" can be disassembled in Z^+ direction as the result is "0" in this direction; and component "*D*" can be disassembled in both Z^+ and Z^- directions.

Here, component "*C*" is disassembled in Z^+ direction firstly, and the remaining combined space interference matrix is shown below:

$$\boldsymbol{S} = \begin{matrix} & A & B & D & \text{Result} \\ A & 000000 & 010011 & 111100 & 111111 \\ B & 100011 & 000000 & 111100 & 111111 \\ D & 111100 & 111100 & 000000 & 111100 \end{matrix} \tag{10}$$

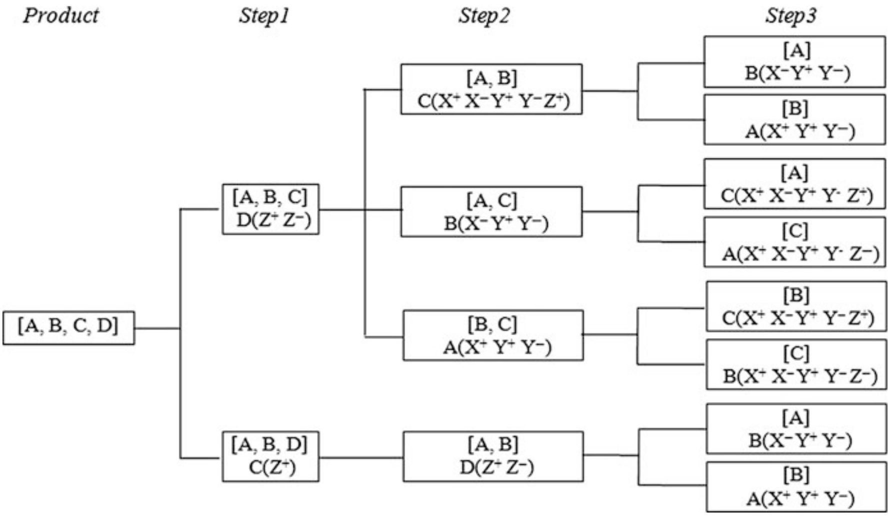

Fig. 6 All the feasible disassembly sequences for the product

From Eq. 10, only component "*D*" can be disassembled in both Z^+ and Z^- directions. Here, component "*D*" is disassembled in Z^+ direction, and the remaining combined space interference matrix is shown below:

$$\boldsymbol{S} = \begin{matrix} & \\ A \\ B \end{matrix} \begin{matrix} \begin{matrix} A & \quad\quad B \end{matrix} \\ \begin{bmatrix} 000000 & 010011 \\ 100011 & 000000 \end{bmatrix} \end{matrix} \begin{matrix} \text{Result} \\ 010011 \\ 100011 \end{matrix} \tag{11}$$

From Eq. 11, components "*A*" and "*B*" can be disassembled in three directions. After disassembling "*A*" in X^+ direction, the product has been disassembled completely. Loop the above analysis processing until all the feasible disassembly sequences of the product are obtained. Based on the above analysis and the developed matrix analysis algorithm, the total feasible disassembly sequences for the product is 192 (30 + 30 + 30 + 30 + 30 + 30 + 6 + 6) (shown in Fig. 6).

The obtained result of all feasible disassembly sequences for the product can be used as a solution space to support our developed PSO-based selective disassembly planning method to search the optimized disassembly sequence based on customer requirements. The details are shown in the following section.

Customizable Decision-Making Model and PSO-Based Selective Disassembly Planning Approach

Customizable Decision-Making Modeling for Selective Disassembly Planning

Disassembly of WEEE involves different stakeholders, such as environmental regulators and remanufacturers. The different levels of targets will lead them to

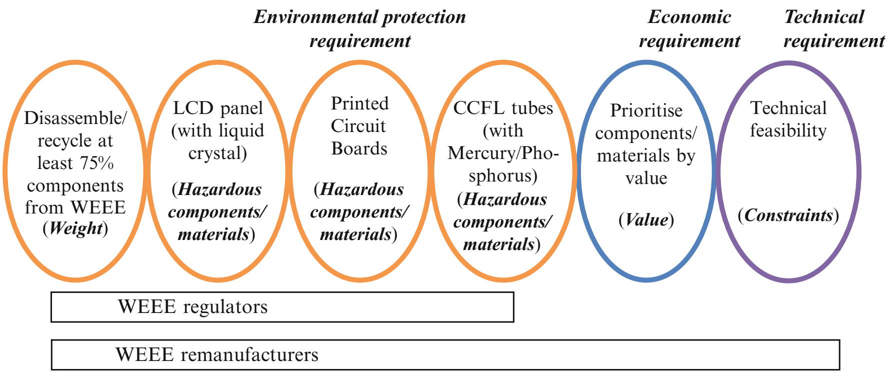

Fig. 7 Criteria used to develop different decision-making models to address various users' needs

adopt or develop different decision-making models. For instance, according to the WEEE Directive, WEEE regulators will check whether remanufacturing companies are able to recycle at least 75 % of WEEE by weight and remove/recover all the hazardous materials. In other words, at least 75 % of WEEE are required to be dismantled to a component level, and all the components containing hazardous materials need to be taken apart from WEEE for further recycling and processing. Apart from fulfilling these fundamental environmental targets, remanufacturers would also improve the economic efficiency by prioritizing valued components during disassembly. In Fig. 7, an example of LCD WEEE is used to illustrate the above scenario.

In order to develop a selective disassembly planning method that is suitable for stakeholders to process various types of WEEE and meet their specific requirements, it is imperative to define customizable decision-making models. The models (disassembly indices and objective) developed in this research are described below.

Disassembly Indices

In the following formulas, two symbols will be used frequently and they are explained here first:

n The number of the total disassembly operations in a plan of a set of WEEE

m The number of the disassembly operations in a selective disassembly plan

Position(Oper(i)) *The position (sequence) of the ith disassembly operation in a disassembly plan*

- *Selective Disassembly Plan (DP) and Disassembly Operation* (Oper(i))

A set of WEEE can be fully disassembled using a disassembly plan. The number of all the operations in the plan is n. A selective disassembly plan (DP), which consists of a set of disassembly operations, is a part of the above complete operations. The number of the selected operations is m, and the i th operation is denoted as Oper(i). DP can be represented as

$$\mathrm{DP} = \bigcup_{i=1}^{m} \left(\mathrm{Oper}(i), \mathrm{Position}\left(\mathrm{Oper}(i)\right)\right) \tag{12}$$

where ∪ represents the set of disassembly operations and $m \leq n$.

For instance, there are a set of disassembly operations Oper(1), Oper(2), Oper (3), Oper(4), and their positions in *DP* are 4, 2, 1, 3 (e.g., Position(Oper(1)) = 4), so that the sequence of the operations in *DP* is Oper(3), Oper(2), Oper(4), Oper(1).

Meanwhile, Oper(i) has some properties related to the environmental and economic targets defined as follows.

- *Hazardousness* (H(Oper(i))) *and Hazardousness Index* (Index_H)

H(Oper(i)) of the i th disassembly operation is to indicate the level of hazardousness contained in the component(s) removed by the operation from the WEEE. It can be represented in a qualitative means, i.e., high, relatively high, medium, and low, and converted to a quantitative means accordingly, such as (5, 3, 1, 0) for (high, relatively high, medium, low). Index_H of a set of WEEE is to indicate the accumulated hazardousness contained in the component(s) removed by the disassembly operations in the WEEE. Index_H can be computed as below:

$$\mathrm{Index\_}H = \sum_{i=1}^{m} \left(H(\mathrm{Oper}(i)) * \mathrm{Position}(\mathrm{Oper}(i))\right) \tag{13}$$

A smaller Index_H will be beneficial. The function of multiplying H(Oper(i)) and its position Position(Oper(i)) in *DP* is to ensure that the disassembly operations with higher hazardousness (i.e., H(Oper(i))) are arranged earlier in *DP* to achieve a smaller Index_H.

For instance, the hazardousness of Oper(1), Oper(2), Oper(3), Oper(4) is (high, low, medium, relatively high), respectively, which can be converted to (5, 0, 1, 3). The positions of the operations in *DP* are (4, 2, 1, 3). Therefore, the hazardousness index of *DP* is (5*4 + 0*2 + 1*1 + 3*3) = 30. If the positions of the operations are rearranged as (1, 4, 3, 2), then the hazardousness index is (5*1 + 0*4 + 1*3 + 3*2) = 14. The latter is lower than the earlier since the operations with higher hazardousness are arranged earlier in the latter. In objective defined later on, a weighted minimum hazardousness index will be pursued to ensure the operations to remove the most hazardous components will be arranged as early as possible to improve the efficiency of hazardousness removal in a selective disassembly plan.

- *Potential Recovery Value* (V(Oper(i))), *Disassembly Time* (T(Oper(i))), *and Potential Value Index* (Index_V)

V(Oper(i)) of the i th disassembly operation is to indicate the potential recovery value of the component(s) disassembled from the WEEE by the operation. The disassembled component(s) could be reusable so that V(Oper(i)) can be represented as the depreciation value of the equivalent new component(s). T(Oper(i)) represents the time spent for the disassembly operation Oper(i). Index_V of a set of WEEE is to indicate the accumulated potential value index by the disassembly operations in the WEEE. Index_V can be computed as below:

$$\text{Index\_}V = \sum_{i=1}^{m} \left(\left(V(\text{Oper}(i))/T(\text{Oper}(i)) * \text{Position}\left(\text{Oper}(i)\right)\right)\right) \tag{14}$$

A smaller Index_V will be beneficial. V(Oper(i))/T(Oper(i)) represents the potential value recovery efficiency of Oper(i). The function of multiplying V(Oper(i))/T(Oper(i)) and its position Position(Oper(i)) in *DP* is to ensure that the disassembly operations with higher V(Oper(i))/T(Oper(i)) are arranged earlier to achieve a smaller Index_V so as to achieve a higher efficiency of potential value recovery for a selective disassembly plan.

- *Weight Removal* (W(Oper(i))) *and Weight Removal Index* (Index_W)

W (Oper(i)) is to indicate the level of the removed weight by the i th disassembly operation from the WEEE. It can be represented by the weight of the component (s) disassembled by the operation. Index_W of a set of WEEE is to indicate the accumulated weight removal index by the disassembly operations in the WEEE. Index_W can be computed as below:

$$\text{Index\_}W = \sum_{i=1}^{m} \left(W(\text{Oper}(i)) * \text{Position}(\text{Oper}(i))\right) \tag{15}$$

Similarly, a smaller Index_W will be beneficial. The function of multiplying W (Oper(i)) and its position Position(Oper(i)) in *DP* is to ensure that the disassembly operations with higher W(Oper(i)) are arranged earlier to achieve a smaller Index_W in order to improve the efficiency of weight removal in a selective disassembly plan.

Disassembly Constraints

During the process of disassembly, there are some technical constraints to specify precedent relationships between disassembly operations. An example in Fig. 8 is used to illustrate the concept. There is a single disassembly direction for components

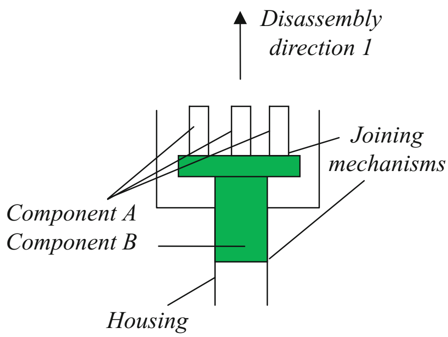

Fig. 8 Examples of constraints during disassembly

A and B. Geometrically, it can dismantle either the joining mechanism between component B and housing first (Oper(1)) or the joining mechanism between components A and B first (Oper(2)). However, from the technical point of view, it is recommended to remove the joining mechanism between component B and housing first, considering that the disassembly of the second joining mechanism needs more operation space. Therefore, Oper(1) is constrained to be prior to Oper(2) technically.

Decision-Making Objective

Disassembly decision-making will be modeled as a constraint-based optimization problem. The objective can be customized to address the different requirements of stakeholders through providing weight setting by users. The objective is represented below:

$$\begin{aligned}&\text{Mimimise}(\text{Index\_}H, \text{Index\_}V, \text{Index\_}W)\\&\quad = \text{Minimise}(w_1 * \text{Index\_}H + w_2 * \text{Index\_}V + w_3 * \text{Index\_}W)\end{aligned} \tag{16}$$

where $w_1 - w_3$ are the weights. The setting of weights can be used to reflect importance. A higher weight means more attentions will be paid to that index, and a zero value means such the index will not be considered. In order to rationalize the model, the three indices are required to be normalized to be in the same measurement scale. The late case studies can illustrate the normalization process.

Improved Particle Swarm Optimization Algorithm

The different selection and optimization sequencing of disassembly operations for a set of WEEE usually brings forth a large search space. Conventional algorithms are often incapable of optimizing the problem. To address it effectively, some modern optimization algorithms, such as genetic algorithm (GA) and simulated annealing (SA), have been developed to quickly identify an optimized solution in a large search space through some evolutional or heuristic strategies. In this research, an improved algorithm based on a modern intelligent algorithm, i.e., PSO, has been applied to facilitate the search process. Moreover, the improved PSO has been also compared with GA and SA for this disassembly planning problem to show the characteristics of the algorithms. For more details of GA and SA implementation, refer to (Li et al. 2002; Li and McMahon 2007; Reddy et al. 1999).

A classic PSO algorithm was inspired by the social behavior of bird flocking and fish schooling (Kennedy and Eberhart 1995). Three aspects will be considered simultaneously when an individual fish or bird (particle) makes a decision about where to move: (1) its current moving direction (velocity) according to the inertia of the movement, (2) the best position that it has achieved so far, and (3) the best position that all the particles have achieved so far. In the algorithm, the particles form a swarm, and each particle can be used to represent a potential disassembly plan of a problem. The velocity and position of a particle (disassembly plan) will be computed below:

$$V_i^{t+1} = w * V_i^t + c_1 * \text{Rand}(1) * \left(P_i^t - X_i^t\right) + c_2 * \text{Rand}(1) * \left(P_g^t - X_i^t\right) \tag{17}$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{18}$$

$$X_i = (X_{i1}, X_{i2}, \ldots, X_{iN}) \tag{19}$$

$$V_i = (V_{i1}, V_{i2}, \ldots, V_{iN}) \tag{20}$$

Here, i is the index number of particles in the swarm, t is the iteration number, and V and X are the velocity vector and the position vector of a particle, respectively. For an N-dimensional problem, V and X can be represented by N particle dimensions as formulas Eqs. 14 and 15 show. P_i is the local best position that the i th particle has achieved so far; P_g is the global best position that all the particles have achieved so far; W is the inertia weight to adjust the tendency to facilitate global exploration (smaller w) and the tendency to facilitate local exploration to fine-tune the current search area (larger w); Rand(1) returns a random number in [0, 1]; and c_1 and c_2 are two constant numbers to balance the effect of P_i and P_g.

In each iteration, the position and velocity of a particle can be adjusted by the algorithm that takes the above three considerations into account. After a number of iterations, the whole swarm will converge at an optimized position in the search space. A classic PSO algorithm can be applied to optimize the disassembly planning models in the following steps:

1. Initialization:
   - Set the size of a swarm, e.g., the number of particles "*Swarm_Size*" and the max number of iterations "*Iter_Num*."
   - Initialize all the particles (a particle is a disassembly plan *DP*) in a swarm. Calculate the corresponding indices and objective of the particles according to formulas Eqs. 12, 13, 14, 15, and 16 (the result of the objective is called *fitness* here).
   - Set the local best particle and the global best particle with the best *fitness*.
2. Iterate the following steps until "*Iter_Num*" is reached:
   - For each particle in the swarm, update its velocity and position values.
   - Decode the particle into a disassembly plan in terms of new position values and calculate the *fitness* of the particle. Update the local best particle and the global best particle if a lower *fitness* is achieved.
3. Decode the global best particle to get the optimized solution.

However, the classic PSO algorithm introduced above is still not effective in resolving the problem. There are two major reasons for it:

- Due to the inherent mathematical operators, it is difficult for the classic PSO algorithm to consider the different arrangements of operations, and therefore the particle is unable to fully explore the entire search space.
- The classic algorithm usually works well in finding solutions at the early stage of the search process (the optimization result improves fast), but is less efficient during the final stage. Due to the loss of diversity in the population, the particles move quite slowly with low or even zero velocities, and this makes it hard to reach the global best solution. Therefore, the entire swarm is prone to be trapped in a local optimum from which it is difficult to escape.

To solve these two problems and enhance the capability of the classic PSO algorithm to find the global optimum, new operations, including crossover and shift, have been developed and incorporated in an improved PSO algorithm. Some modification details are depicted below:

1. New operators in the algorithm:
   - Crossover. Two particles in the swarm are chosen as parent particles for a crossover operation. In the crossover, a cutting point is randomly determined, and each parent particle is separated as left and right parts of the cutting point. The positions and velocities of the left part of parent 1 and the right part of parent 2 are reorganized to form child 1. The positions and velocities of the left part of parent 2 and the right part of parent 1 are reorganized to form child 2.
   - Shift. This operator is used to exchange the positions and velocities of two operations in a particle in a random position so as to change their relative positions in the particle.
2. Escape method.

During the optimization process, if the iteration number of obtaining the same best fitness is more than 10, then the crossover and shift operations are applied to the best particle to escape from the local optima.

A general diagram to show the above flow is shown in Fig. 9.

Case Studies on LCD Televisions

Televisions can be generally classified into five groups: CRT, LCD, PDP, OLED, and RP. The LCD televisions have been developed quickly over the past decades, and they are now sharing the biggest market (e.g., the global market figures for the LCD televisions are forecasted to surpass $80 billion in 2012; Ryan et al. 2011). An LCD television produces a black and colored image by selectively filtering a white light. The light is typically provided by a series of cold cathode fluorescent lamps (CCFLs) at the back of the screen, although some displays use white or colored LED. The LCD televisions studied here are produced by the Changhong Electronics

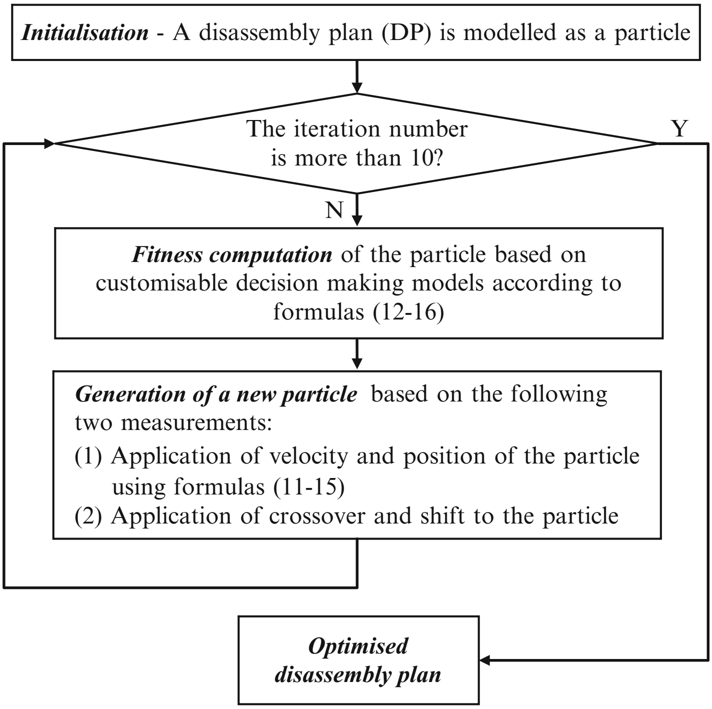

Fig. 9 The general workflow of the PSO-based disassembly plan optimization

Company, Ltd. from China, which is the biggest television producer in China. The company provides information about LCD televisions of the type of LC24F4, such as the bill of materials (BoMs), the exploded view, the mass of each part, and the detailed assembly processes. The structure of the LCD television is shown in Fig. 10a, b. The typical exploded view of an LCD television is shown in (c). As shown in (d), an LCD television is typically assembled by three main parts: front cover assembly part, back cover assembly part, and base assembly part. All feasible disassembly sequences for these three parts are generated in the following section.

Solution Space Generation

Base Assembly Part

The base assembly part of the LC24F4 LCD television is shown in Fig. 11. It is composed of nine parts: (*A*) metal fixing plate, (*B*) metal washer 1, (*C*) metal washer 2, (*D*) top metal support, (*E*) cylindrical metal support 1, (*F*) cylindrical metal support 2, (*G*) toughened glass seat, (*H*) steel plate, and (*I*) rubber gasket. The space interference matrices to represent the base assembly part in six directions are shown below:

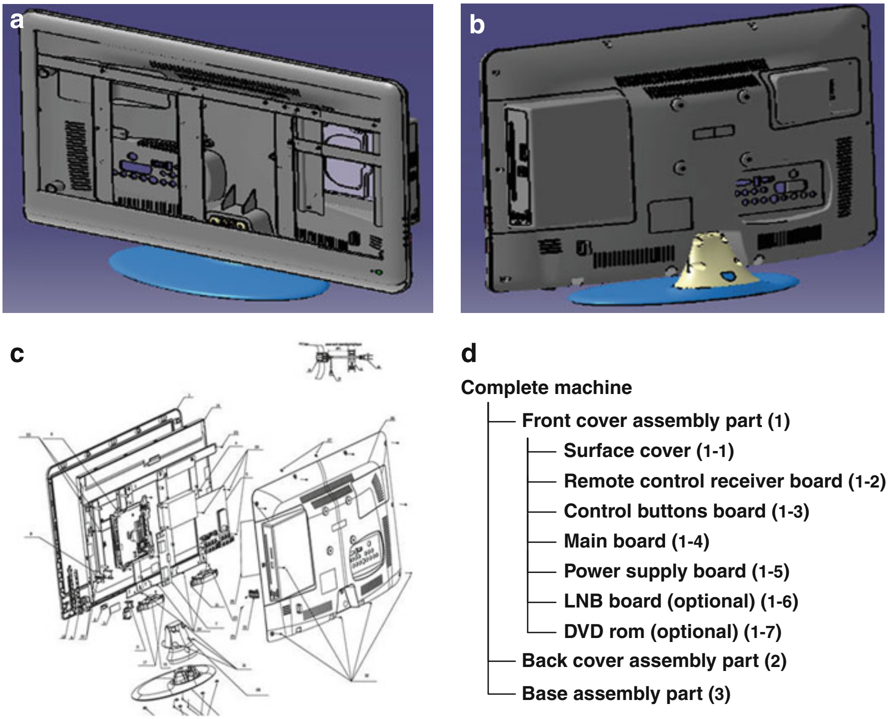

Fig. 10 The LC24F4 LCD television and its structures (**a**) Front view of the LCD television framework (**b**) Back view of the LCD television framework (**c**) Typical exploded view of the LCD television structure (**d**) Part of the BoMs of the LCD television

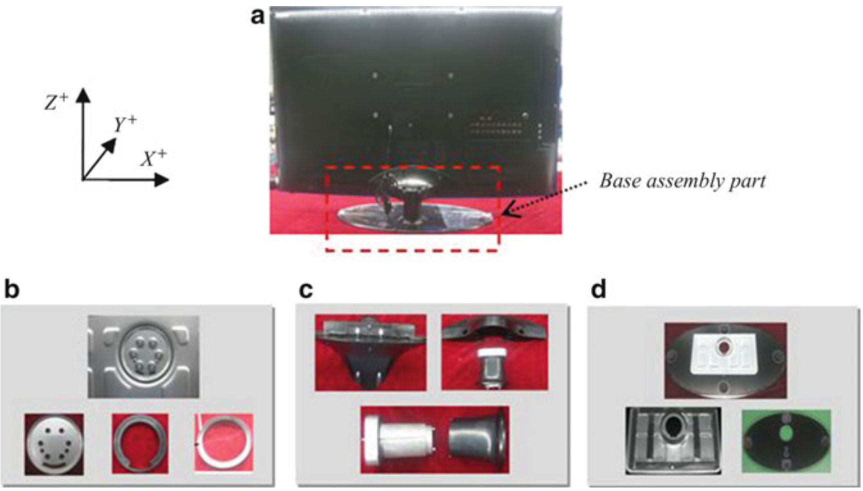

Fig. 11 The base assembly part of the LC24F4 LCD television: (**a**) base assembly part, (**b**) components A, B, C, (**c**) components D, E, F, and (**d**) components G, H, I

$$
\boldsymbol{S}_{X^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right]
\end{array}
\quad
\boldsymbol{S}_{X^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right]
\end{array}
$$

$$
\boldsymbol{S}_{Y^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right]
\end{array}
\quad
\boldsymbol{S}_{Y^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right]
\end{array}
$$

$$
\boldsymbol{S}_{Z^+} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right]
\end{array}
\quad
\boldsymbol{S}_{Z^-} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} A & B & C & D & E & F & G & H & I \end{array} \\
\left[\begin{array}{ccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right]
\end{array}
$$

After combining the above six matrices and using Boolean operator "OR" in rows, the obtained result is as follows:

$\boldsymbol{S} =$

	A	B	C	D	E	F	G	H	I	Result
A	000000	000010	000010	000010	000010	000010	111110	111110	111100	111110
B	000001	000000	000010	000010	000010	000010	111110	111110	111100	111111
C	000001	000001	000000	000010	000010	000010	111110	111110	111100	111111
D	000001	000001	000001	000000	111101	111101	111101	111101	000000	111101
E	000001	000001	000001	111110	000000	111101	000001	000001	000000	111111
F	000001	000001	000001	111110	111110	000000	111110	111110	111100	111111
G	111101	111101	111101	000010	000010	000010	000000	111101	000001	111111
H	111101	111101	111101	000010	000010	000010	111110	000000	111100	111111
I	000000	000000	000000	000000	000000	000000	000010	111100	000000	111110

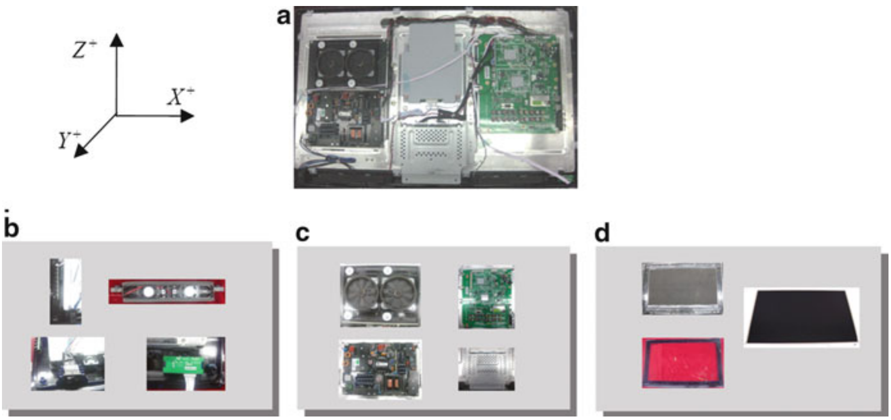

Fig. 12 The front assembly part of the LC24F4 LCD television: (**a**) front assembly part, (**b**) components J, K, L, M, (**c**) components N, O, P, Q, and (**d**) components R, S, T

Based on the developed matrix analysis algorithm, there are a total of 918 feasible disassembly sequences for the base assembly part.

Front Cover Assembly Part

The front cover assembly part of the LC24F4 LCD television is shown in Fig. 12. It is composed of 11 parts: (J) control button, (K) power switch, (L) side loudspeaker, (M) control receiver board, (N) positive loudspeaker, (O) power supply board, (P) main board, (Q) metal board, (R) metal mounting plate, (S) surface frame, and (T) LCD screen.

The space interference matrices to represent the front cover assembly part in six directions are shown below:

$$S_{X^+} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} J\ K\ L\ M\ N\ O\ P\ Q\ R\ S\ T \\ \left[\begin{array}{ccccccccccc} 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{array}\right] \end{array} \quad S_{X^-} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} J\ K\ L\ M\ N\ O\ P\ Q\ R\ S\ T \\ \left[\begin{array}{ccccccccccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{array}\right] \end{array}$$

$$S_{Y^+} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} \begin{array}{ccccccccccc} J & K & L & M & N & O & P & Q & R & S & T \end{array} \\ \left[\begin{array}{ccccccccccc} 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&1&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 1&1&1&1&1&1&1&1&0&0&0 \\ 1&1&1&1&1&1&1&1&1&0&1 \\ 1&1&1&1&1&1&1&1&1&0&0 \end{array}\right] \end{array}$$

$$S_{Y^-} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} \begin{array}{ccccccccccc} J & K & L & M & N & O & P & Q & R & S & T \end{array} \\ \left[\begin{array}{ccccccccccc} 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&1&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&0&1&1 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0 \end{array}\right] \end{array}$$

$$S_{Z^+} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} \begin{array}{ccccccccccc} J & K & L & M & N & O & P & Q & R & S & T \end{array} \\ \left[\begin{array}{ccccccccccc} 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&1&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 1&0&0&0&1&1&1&1&0&1&1 \\ 0&0&0&0&0&0&0&0&1&0&1 \\ 0&0&0&0&0&0&0&0&1&1&0 \end{array}\right] \end{array}$$

$$S_{Z^-} = \begin{array}{c} \\ J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{array} \begin{array}{c} \begin{array}{ccccccccccc} J & K & L & M & N & O & P & Q & R & S & T \end{array} \\ \left[\begin{array}{ccccccccccc} 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0 \\ 1&1&1&1&1&1&1&1&0&1&1 \\ 0&0&0&0&0&0&0&0&1&0&1 \\ 0&0&0&0&0&0&0&0&1&1&0 \end{array}\right] \end{array}$$

After combining the above six matrices and using Boolean operator "OR" in rows, the obtained result is shown below:

$S =$

	J	K	L	M	N	O	P	Q	R	S	T	Result
J	000000	100000	100000	100000	000000	000000	000000	000000	101111	000100	000100	101111
K	010000	000000	100000	100000	000000	000000	000000	000000	111110	000100	000100	111110
L	010000	010000	000000	100000	000000	001000	001000	000000	111110	000100	000100	111110
M	010000	010000	010000	000000	000000	000000	000000	000000	111110	000100	000100	111110
N	000000	000000	000000	000000	000000	000001	000000	000000	110111	000100	000100	111111
O	000000	000000	000100	000000	000010	000000	100000	100000	110111	000100	000100	110111
P	000000	000000	000000	000000	010000	010000	000000	010000	110111	000100	000100	110111
Q	000000	000000	000000	000000	000000	010000	100000	000000	110111	000100	000100	110111
R	011011	111001	111001	111001	111011	111011	111011	111011	000000	110111	110111	111111
S	001000	001000	001000	001000	001000	001000	001000	001000	111011	000000	111011	111011
T	001000	001000	001000	001000	001000	001000	001000	001000	111011	110111	000000	111111

Based on the developed matrix analysis algorithm, there are a total of 7096320 feasible disassembly sequences for the front assembly part.

Fig. 13 The back cover assembly part of LCD television

Back Cover Assembly Part

The back cover assembly part of an LC24F4 LCD television is composed of three parts: (U) back cover, (V) cover plate, and (W) support (shown in Fig. 13).

The space interference matrices to represent the back cover assembly part in six directions are shown below:

$$\boldsymbol{S}_{X^+} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{array} \quad \boldsymbol{S}_{X^-} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \end{array}$$

$$\boldsymbol{S}_{Y^+} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{array} \quad \boldsymbol{S}_{Y^-} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{array}$$

$$\boldsymbol{S}_{Z^+} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{array} \quad \boldsymbol{S}_{Z^-} = \begin{array}{c} \\ J \\ K \\ L \end{array} \begin{array}{c} \begin{array}{ccc} J & K & L \end{array} \\ \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{array}$$

After combining the above six space interface matrices and using Boolean operator "OR" in rows, the combined matrix is as follows:

$$\boldsymbol{S} = \begin{array}{c} \\ U \\ V \\ W \end{array} \begin{array}{c} \begin{array}{ccc} U & V & W \end{array} \\ \begin{bmatrix} 000000 & 110111 & 101111 \\ 111011 & 000000 & 100000 \\ 011111 & 010000 & 000000 \end{bmatrix} \end{array} \begin{array}{c} \text{Result} \\ 111111 \\ 111011 \\ 011111 \end{array}$$

Based on the developed matrix analysis algorithm, the number of feasible disassembly sequences for the back cover assembly part is 4.

Table 1 Comparison between our developed method and others

Our developed method: 450 × 7096320 × 4 = **2.6058e**$^{+10}$ (all feasible disassembly sequences)
Others: 23! = 23 × 22. . .2 × 1 = **2.5852e**$^{+22}$ (all disassembly sequences)
Searching range reduced: 2.5852e^{+22}/3776400 = **9.9209e**$^{+11}$ times

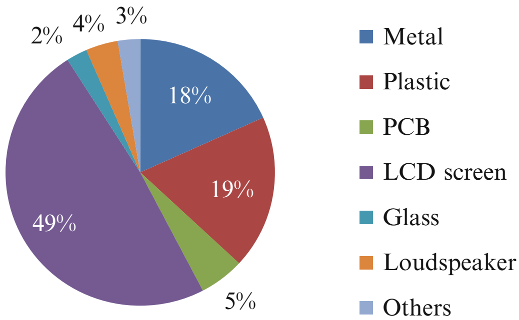

Fig. 14 The component/material composition of the LCD television

Based on the above analysis, the developed solution space generation approach can find that the value of all the feasible disassembly sequences of the LC24F4 LCD television is **2.6058e**$^{+10}$ = 918 × 7096320 × 4(base assembly part × front cover assembly part × back over assembly part). Compared with all disassembly sequences, which is 23! = 23 × 22. . .2 × 1 = **2.5852e**$^{+22}$, the searching range for a disassembly planning algorithm to find the optimized disassembly sequence of the LC24F4 LCD television is reduced to about **9.9209e**$^{+11}$ times (shown in Table 1). All the results from the above have been generated using the algorithm in MATLAB language. It is obvious that the developed approach can dramatically reduce the searching range and obtain all feasible disassembly sequences of the LC24F4 LCD television, which can be used as a solution space to support our developed PSO-based selective disassembly planning method to achieve better economic value and environmental protection requirements within an acceptable runtime.

Selective Optimizations and Comparisons

The mass of the LC24F4 LCD television is 5963.8 g, and the main component/material composition is shown in Fig. 14, in which the percentage is represented in terms of the ratio of mass. Among the component/material compositions, the PCBs (printed circuit boards, which are mainly main boards and power supply boards) and LCD screens are quite complex. Other components/materials include cables, wires, pins, switches, and rubbers. The cables, wires, pins, and switches consist of plastics that are usually polyvinyl chloride (PVC) and nonferrous mainly copper (Cu) and aluminum (Al).

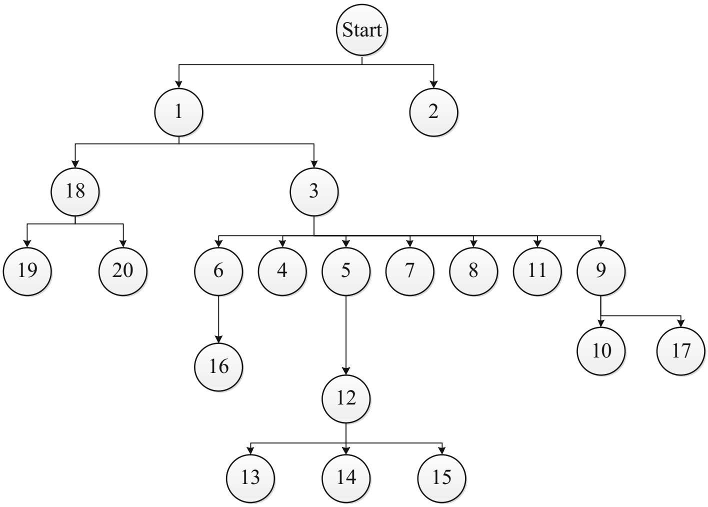

Fig. 15 The disassembly constraint graph

Based on the BoMs of the LC24F4 LCD television, the process of disassembly can be planed. Figure 15 is used to represent the constraints of the disassembly plan and called the disassembly constraint graph. Except for the disassembly constraint graph, there are several other methods to represent the disassembly constraints, such as disassembly tree, state diagram, and and/or graph (Lambert and Gupta 2005). In the graph, nodes represent operations and arcs represent the precedence constraint relationships between operations. Meanwhile, each operation is defined with several properties, such as disassembly operation number, disassembly operation time, component(s) (name, amount, and mass) to be disassembled by each operation, and potential recovered component(s)' mass, value, and hazardousness. Firstly, one of the disassembly plans of the LC24F4 LCD television is (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20). This plan is called "an initial plan" to be used in the following scenarios for the comparisons with an optimized plan for a better understanding of the optimization process. Table 2 lists the properties of the disassembly process according to the disassembly operation number.

Scenario 1 for Selective Optimization

It is aimed to determine a selective optimization disassembly plan (part of the full disassembly plan) to meet the environmental protection targets (100 % hazardousness removal and 75 % component disassembled for the whole WEEE) and achieve the optimized potential recovery value (all the three weights in formula Eq. 15 were set 1). The input data is shown in Table 2.

In Fig. 16a, the disassembly planning selection and optimization process is shown. During the computation process, results were normalized, i.e., the index result of each operation was converted as the percentage of the overall results of all the operations. The results in the Y-axis were also accumulated for the operations.

Table 2 Disassembly operations and some properties of the LC24F4 LCD television

Disassembly operations	Time (s)	Components	Mass (g)	Potential value (Yuan)	Hazardousness removal
1. Unscrew and remove base part	86.4	Base part	1.8	0.0119	Low
		M4x12	1.6	0.0106	
2. Unscrew and remove cover plate	86.4	4x10BTECh	11.2	0.0739	Low
		Cover plate	23.0	0.1840	
		3x10KTHCh	0.6	0.0004	
3. Remove back cover part	43.2	Support structure	15.6	0.1248	Low
4. Disassemble back cover part	21.6	Back cover	723.8	1.7904	Low
		Insulation board	25.0	0.2280	
5. Remove wire with pin	86.4	Wire with pin	50.0	0.1000	Low
6. Remove power switch part	43.2	Power switch part	5.0	0.0100	Low
7. Remove control button part	43.2	Control button	3.7	0.0050	Low
		Control button part	5.5	0.0050	
8. Unscrew and remove main board	129.6	Main board	196.0	0.7908	Relatively high
		M3x8GB/T9074.4	3.0	0.0021	
		Insulating washer	3.0	0.0100	
9. Unscrew and remove loudspeaker part	86.4	Loudspeaker part	60.0	1.3000	Low
		M3x8GB/T9074.4	2.0	0.0040	
10. Unscrew and remove power supply board and insulating board	86.4	Power supply board	118.0	0.6466	Medium
		Insulating board	25.0	0.1520	
		M3x8GB/T9074.4	0.5	0.0033	
		M4x8GB/T9074.4	0.6	0.0004	
11. Unscrew and remove metal support	86.4	Metal support	183.0	1.2078	Low
		M4x8GB/T818	2.4	0.0158	
12. Unscrew	86.4	4x8BTHCh	7.2	0.0475	Low
		Clamping bush	24.0	0.1584	
13. Remove loudspeaker	43.1	Loudspeaker	77.8	0.0600	Low
14. Remove remote control receiver board	21.6	Remote control receive board	3.0	0.4000	Medium

(*continued*)

Table 2 (continued)

Disassembly operations	Time (s)	Components	Mass (g)	Potential value (Yuan)	Hazardousness removal
15. Separate surface frame and LCD screen	21.6	Surface frame	270.8	1.1000	High
		LCD screen	2900.0	9.6684	
		Metal mounting plate	639.0	1.2170	
16. Disassemble power switch part	64.8	Power switch	5.0	0.0100	Low
		Power wire	75.5	0.1000	
		Wire with pin	5.0	0.0100	
17. Disassemble loudspeaker part	64.8	Loudspeaker	152.0	0.6000	Low
		Support	95.0	0.0200	
		Washer	2.0	0.0070	
		4x8BTHCh	2.4	0.0158	
18. Disassemble base part	86.4	Metal washer 1	10.0	0.0660	Low
		Metal washer 2	10.0	0.0660	
		Metal fixing plate	15.0	0.0990	
		M4x12GB/T818	2.4	0.0158	
19. Disassemble brace part	86.4	Metal support	25.0	0.1650	Low
		Plastic support 1	30.0	0.2400	
		Plastic support 2	20.0	0.1600	
		M4x12GB/T818	2.4	0.0158	
20. Disassemble seat part	64.8	Toughened grass seat	150.0	0.3300	Low
		Steel plate	50.0	0.0640	
		Rubber gasket	20.0	0.0200	

The hazardousness removal, weight removal, and potential recovery value for the initial plan and an optimized plan are shown in (b), (c), and (d), respectively. In (b), a 100 % hazardousness removal target will be achieved after 13 disassembly operations for the optimized plan. In (c), a target to achieve 75 % component disassembled by weight (of the total weight of the WEEE) took 6 operations for the optimized plan. In (d), the result of potential recovery value divided by spent time for each operation is shown, which is a target to achieve the most potential recovery value within the shortest time. To meet the environmental protection targets of removing 100 % components with hazardous materials and 75 % components by weight to be disassembled, the first 13 disassembly operations were selected from the optimized plan as the selective optimized plan. Meanwhile, the potential recovery value and spent time for this plan were optimized in this selective plan.

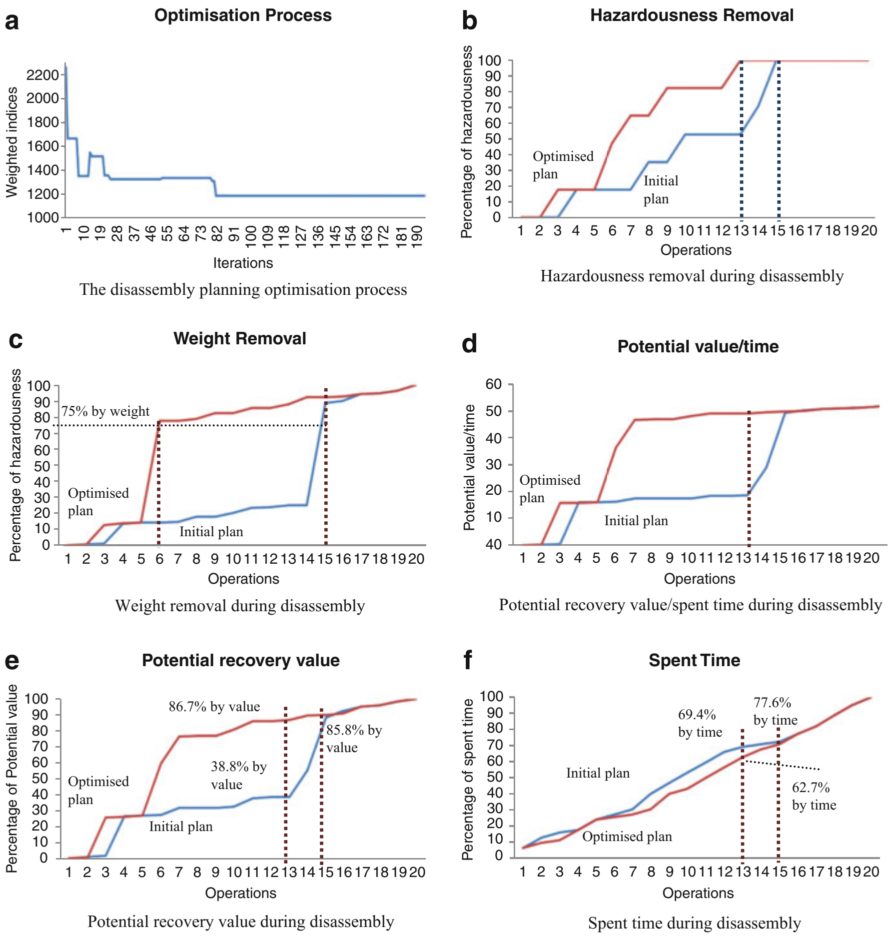

Fig. 16 Disassembly planning optimization with customizable decision-making models (all weights are 1)

In (b) and (c), it is shown that the initial plan will take 15 disassembly operations to achieve 100 % hazardousness removal and also 15 operations for 75 % components by weight to be disassembled. Therefore, 15 operations are necessary to achieve the environmental protection targets. Therefore, the optimized plan will have 2 less operations. The potential value/time in (d) can be separated and interpreted in (e) and (f). It shows that with the selective optimized plan, the potential recovery values during the disassembly process are 86.7 % (of the total potential value of all the disassembled components in the WEEE) for 13 operations and 38.8 % and 85.8 % for the initial plan after 13 and 15 operations, respectively. With the selective optimized plan, the time spent during the process was 62.7 % (of the total time spent to disassemble the WEEE) for 13 operations and 69.4 % and 77.6 % for the initial plan after 13 and 15 operations, respectively.

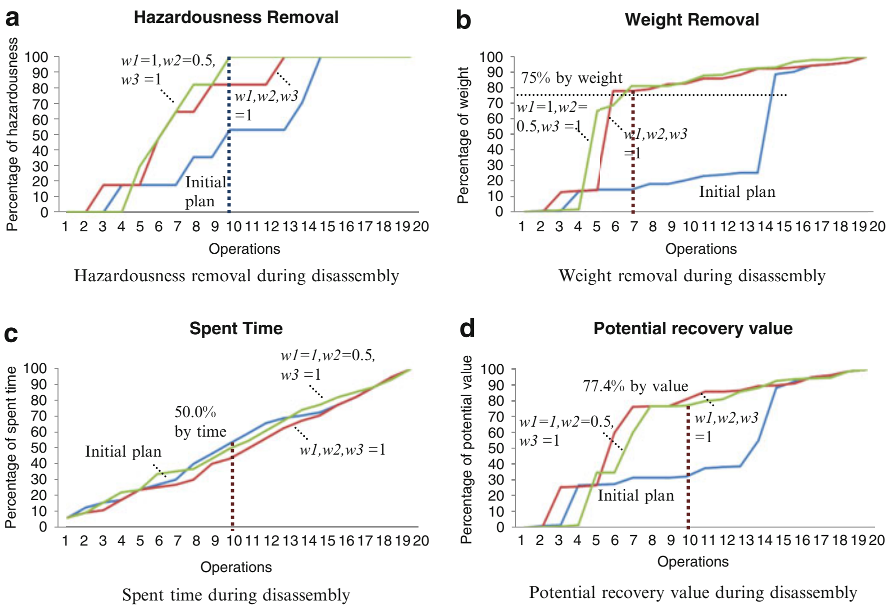

Fig. 17 Disassembly planning optimization with customizable decision-making models (weights are 1, 0.5, 1)

Therefore, if the first 13 operations are selected for both plans, it can be observed that significant potential value is recovered (86.7 % vs. 38.3 %) while less time spent with the optimized solution (62.7 % vs. 69.4 %). If the first 13 operations and 15 operations are selected for both plans respectively, a better potential recovery value (86.7 % vs. 85.8 %) while about 15 % time of the total disassembly time can be saved with the optimized solution (62.7 % vs. 77.6 %). Fifteen percent labor time of disassembling a single set of LCD WEEE stands for 200 s and about 6 h for 100 sets of the LCD WEEE.

Scenario 2 for Selective Optimization

It is aimed to prioritize the environmental protection targets (100 % hazardousness removal and 75 % component disassembled for the whole WEEE) (the weights for the hazardousness index and weight removal index in formula Eq. 15 were set 1 and the weight for potential recovery value 0.5). The input data is shown in Table 2.

In Fig. 17a, a 100 % hazardousness removal target will be achieved after 10 disassembly operations for the optimized plan with this weight setting. In (b), a target to achieve 75 % component disassembled by weight (of the total weight of the WEEE) took seven operations for the optimized plan with this weight setting. Therefore, 10 disassembly operations are needed for the selective optimized plan, compared to 13 operations in scenario 1. In (c), the time spent for the 10 operations is 50.0 % of the total time for the WEEE, which can be compared to the related results in scenario 1, which were 62.7 % and 69.4 % of the total time spent to disassemble the WEEE for the optimized plan with all the weights set to 1 and the initial plan for 13 operations, respectively. In (d), the potential recovery value is 77.4 % of the total potential value of the WEEE for this setting, while the potential recovery values are 86.7 % and 38.8 % of the total potential value of all the disassembled components in the WEEE for the optimized plan and the initial plan in scenario 1, respectively. It can be clearly observed that with the prioritized considerations of hazardousness and weight removal, less operations and time are needed accordingly, while the potential recovery value has to be traded off (from 86.7 % to 77.4 %).

Summary

WEEE has been increasingly customized and diversified, and the selective disassembly planning of WEEE to support remanufacturing decision-making is an important but challenging research issue. In this paper, an effective selective disassembly planning method has been developed to address the issue systematically. The characteristics and contributions of the research include:

- Space interference matrix has been used to represent the space interference relationship of each component in six directions in a Cartesian coordinate system for WEEE. By this way, all the space interference relationships between components of WEEE can be digitally recorded and can be analyzed in the next step.
- A matrix analysis algorithm has been developed to obtain all the feasible disassembly sequences of WEEE by analyzing the six space interference matrices in a 3D environment. It is capable to obtain all the feasible disassembly sequences of WEEE, and the result can be used as a solution space to support a disassembly planning method to achieve better economic value for WEEE within an acceptable runtime.
- An improved PSO algorithm-based selective disassembly planning method with customizable decision-making models has been developed. In the method, the customizable decision-making models embedded with adaptive multi-criteria to meet different stakeholders' requirements have been designed to enable the method flexible and customizable in processing WEEE effectively.
- Based on the intelligent optimization algorithms, the developed method is capable to process complex constraints for different types of WEEE based on a generic and robust process and achieve selective optimized disassembly plans efficiently.
- Industrial cases on the LC24F4 LCD television have been carried out to verify the effectiveness and generalization of the developed research. Different application scenarios and targets have been set to validate and demonstrate that this research is promising for practical problem solving.

Future work will include developing an intelligent automated selective disassembly system with industrial robotic manipulator, cameras, and sensors for WEEE such as LCD televisions.

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