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A Systematic Selective Disassembly Approach for Waste Electrical and Electronic Equipment with Case Study on Liquid Crystal Display Televisions (LCD-TVs)

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Abstract

Waste Electrical and Electronic Equipment (WEEE) is one of the major waste streams in terms of quantity and toxicity, and a critical step in WEEE end-of-life (EoL) processing is through disassembly. Compared with full disassembly, which is a sub-optimal solution due to its high operational cost, selective disassembly is more economic and practical as only selected parts with recycling potential are considered. In this paper, a systematic selective disassembly approach for handling WEEE with a maximum disassembly profit in accordance to the WEEE and Restriction of Hazardous Substances (RoHS) Directives has been developed. Firstly, a space interference matrix is generated based on the interference relationship between individual components in the 3D CAD model of WEEE. A matrix analysis algorithm is then applied to obtain all the feasible disassembly sequences through the obtained space interference matrix in a 3D environment. Secondly, an evaluation and decision-making method is developed to find out an optimal selective disassembly sequence from the obtained feasible disassembly sequences. The evaluation takes into account the disassembly profit and requirements of the WEEE and RoHS Directives, which regulate on recycling rates of different types of products and removal requirements of (i) hazardous, (ii) heavy, and (iii) high-value components. Thus an optimal solution is a selective disassembly

sequence that can achieve the maximum disassembly profit, while complying with the WEEE and RoHS restrictions based on a brute-force search method. Finally, an industrial case on Changhong Liquid Crystal Display Televisions (LCD-TVs) of the type LC24F4 is used to demonstrate the effectiveness of the developed approach.

Keywords

Selective disassembly; The WEEE Directive; The RoHS Directive; LCD-TVs

1. INTRODUCTION

Due to the huge market demand and shorter usage lifecycle of Electrical and Electronic Equipment (EEE), the mounting WEEE is posing a severe threat to the environment and sustainable economy. To tackle this issue, the WEEE Directive together with the RoHS Directive was enacted and became a European Environment Law in February 2003 [1]. They are aimed at encouraging manufacturers to provide cradle-to-grave support to recycle maximum values and reduce environmental hazardousness by reducing the amount of WEEE destined for landfill and eradicating certain hazardous substances from WEEE.

Disassembly is a key process of recycling strategies in the treatment of WEEE. Generally, the approach can be classified as full disassembly and selective disassembly. Full disassembly is to completely disassemble every single part in a waste product. On the other hand, selective disassembly aims to minimise the effort required to separate parts selected for separation or replacement. Unlike full disassembly, selective disassembly allows a partial and

non-sequential disassembly procedure [2-4]. In the past years, there have been many research articles published on full disassembly of WEEE. In the literatures [5-7], some detailed reviews on the full disassembly research were given. However, the high cost of disassembly has impeded the cost effectiveness of the full disassembly approach and has resulted in a research trend towards selective disassembly. Although there are a number of papers reporting research on selective disassembly, a systematic selective disassembly approach for handling WEEE with environmental and economic considerations is still unavailable and highly desirable. In this paper, the focus is on the development of a systematic selective disassembly approach that can maximise the disassembly profit and meet the environmental restrictions simultaneously. The approach incorporates the environment requirements of WEEE/RoHS Directives into decision making to ensure the restricted recycling rates of different products are achieved and all hazardous components from WEEE are removed for further EoL processes. Meanwhile, the cost effectiveness of the disassembly operation is maximised by selecting the optimal disassembly planning based on the proposed evaluation and decision making method. **Figure 1** shows the main flow of the developed approach. A summary of the developed approach is given below:

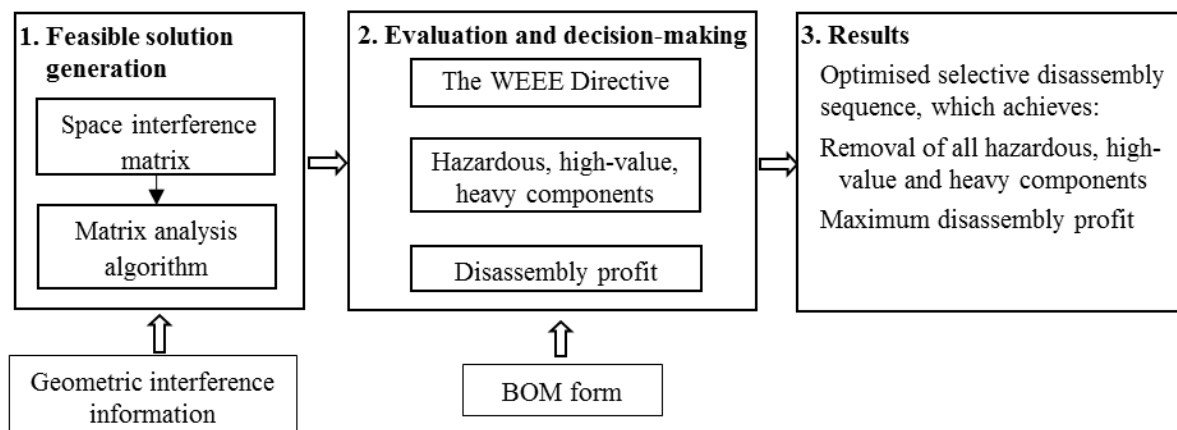


Figure 1 The main flow of the developed approach

- A feasible solution space method is developed to generate all the candidate solutions for further evaluation and decision-making. A space interference matrix is used to represent the space relationships of components of WEEE in six directions in a 3D Cartesian coordinate system. In this manner, all the space interference relationships between components of WEEE can be digitally presented and can be analysed by a matrix analysis algorithm to find out all the feasible disassembly sequences of WEEE.
- An evaluation and decision-making method is developed to identify an optimised selective disassembly sequence for maximising the disassembly profit by considering the recycling rate requirement of the WEEE Directive and removal of all hazardous, high-value and heavy components from WEEE.

A selective disassembly optimisation system based on the above method was implemented and an industrial case study on Changhong Liquid Crystal Display Televisions (LCD-TVs) was performed to validate the developed method. The LCD-TV is selected as the case study due to the fact that it is a typical product of EEE and occupies a significant portion of WEEE (e.g., more than 200 million units are shipped in the global market in 2014 [8]). The performance results on a LCD-TV (type LC24F4) proved the effectiveness of the developed approach.

2. RELATED RESEARCH

Selective disassembly is targeting on singling out hazardous and valuable components of end-of-life (EoL) products. Compared with full disassembly, it is a more economical approach in the practice of recycling WEEE. Recently, attention is being paid towards selective disassembly research, such as LCD-TVs EoL processing. A summary of the previous work is given in **Table 1**, and detailed discussions are presented below.

Kara, et al. [3, 9] developed a selective disassembly method by modifying the typical rule-based question answer method proposed by Nevins and Whitney [29] for assembly sequence generation. It provided a graphical representation of disassembly sequences at the different stages of the process, which allows the user to visualise the disassembly process. Two cases studies, i.e., a single-hole punch and a washing machine, were used to explain the concept and efficiency of the methodology. Garcia, et al. [10] presented a method to determine low-cost selective disassembly sequences. The algorithm computes the minimum distances from the exterior components of the assembly to the rest of components. A set of partial disassembly sequences is obtained by finding minimum spanning trees in the precedence graph. Behdad, et al. [11] presented a method on simultaneous selective disassembly and EoL decision-making for products. It integrates a transition matrix with mixed integer linear programming to determine the extent to which products should be disassembled and the optimal EoL strategy for each resultant component. Two cell phone products were used to illustrate the research. ElSayed, et al. [12] presented an evolutionary algorithm for generating optimal sequences for selective disassembly of EoL products. A Genetic Algorithm was utilised to obtain economically and environmentally sustainable disassembly sequences. Srinivasan and Gadh [13-14] used a geometric algorithm to determine an optimal disassembly sequence for selected components with minimal component removals. The search space of the algorithm is reduced by analysing a subset of components in the assembly. Smith and Chen [15-16] presented a rule-based recursive method for finding an optimal selective disassembly sequence to increase products' recyclability and maintainability. Based on four matrices and five disassembly rules, the method can eliminate unrealistic and uncommon disassembly sequences and find optimal selective disassembly sequences for complex assemblies effectively.

LCD-TVs are one of the most important WEEE. The requirement for recycling LCD-TVs is increasing rapidly as the huge amount of LCD-TVs is to be replaced or in the end of their useful life sooner or later. There are several papers reporting disassembly research on LCD-TVs. Ryan et al. [17] presented an overview of the LCD assembly and detailed material composition of the LCD structure. It investigated the best approach to recycle or disassemble LCD with a hybrid system of manual and automated processes. Umeda et al. [18-19] presented a recyclability evaluation method to evaluate LCD-TVs recyclability in product life cycles at the design stage. Firstly, it describes an EoL scenario of the product, and then to calculate the recyclability rate of the product based on the described EoL scenario. A case study of LCD-TVs was used and the result shows that recyclability of LCD-TVs depends on its EoL processes and material constitution. Chiodo et al. [20] investigated the technical feasibility of removing LCD screens using the smart materials technology. An LCD bracket made from shape memory polymer was used to separate LCD screens from Printed Circuit Boards (PCBs). Li, et al. [2, 21] developed a Particle Swarm Optimisation (PSO)-based selective disassembly planning method embedded with customisable decision making models and a novel generic constraint handling algorithm. The method is flexible for customised decision modelling and is capable of handling complex constraints to achieve better economic value and environmental protection requirements. LCD-TVs have been used to demonstrate the effectiveness and robustness of the developed method. Further research is expected to develop a set of more systematic criteria to evaluate the different stages of remanufacturing in terms of environment and economy.

Table 1 A summary of selective disassembly and disassembly research on LCD-TVs

<i>Works</i>	<i>Selective disassembly</i>	<i>Disassembly research on LCD-TVs</i>	<i>Major characteristics</i>
--------------	------------------------------	--	------------------------------

Kara et al. [3, 9]	○		A graphical representation of disassembly sequences at different stages of the process was provided. It allows the user to visualise the selective disassembly process
Garcia et al. [10]	○		A method was developed to determine low-cost selective disassembly sequences
Behdad et al. [11]	○		A method was developed to simultaneous selective disassembly and EoL decision-making for products
ElSayed et al. [12]	○		A Genetic Algorithm was utilised to obtain economically and environmentally sustainable selective disassembly sequences for EoL products
Srinivasan and Gadh. [13-14]	○		A geometric algorithm was used to find out the optimal disassembly sequence for the selected component with minimal component removals
Smith and Chen. [15-16]	○		The developed method can eliminate unrealistic and uncommon disassembly sequences and find out optimal selective disassembly sequences for complex assemblies effectively
Ryan et al. [17]		○	An overview was presented for the LCD assembly and detailed material composition of the LCD structure
Umeda et al. [18-19]		○	A recyclability evaluation method was developed to evaluate LCD-TV's recyclability in product life cycles at the design stage
Chiodo et al. [20]		○	An LCD bracket made from shape memory polymer was used to separate LCD screens from PCBs
Li et al. [2, 21]	○	○	The developed method is capable of handling complex constraints to achieve better economic value and environmental protection requirements

As mentioned in the Introduction, there still lacks a systematic selective disassembly approach to handle WEEE to meet the environmental and economic requirements. The work in this paper is to develop a systematic selective disassembly approach to achieve better economic value and meet the environmental protection requirements of the WEEE/RoHS Directives.

3. METHODOLOGY AND CHARACTERISTICS

The overview of the developed methods is presented as follows:

- A feasible solution generation method is developed to find out all the feasible disassembly sequences of WEEE by analysing the space interference matrices in a 3D environment.

- An evaluation and decision-making method is devised to identify the optimised disassembly sequence in achieving better economic value and environmental protection requirements.
- An industrial case study on LCD-TVs is carried out to verify and demonstrate the performance of the developed methods.

The developed methods are shown in **Figure 2**. The details are described below.

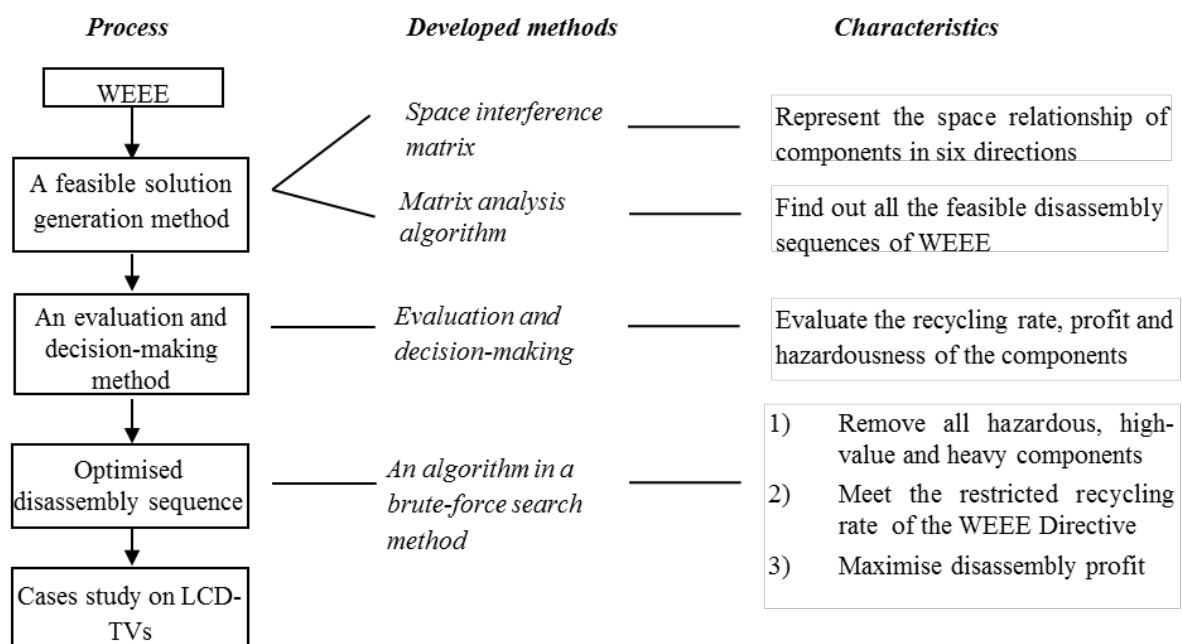


Figure 2 The process of the developed methods

3.1 A Feasible Solution Generation Method

The development of the feasible solution generation method is carried out in two phases.

- Phase 1 is to generate a space interference matrix based on a 3D CAD model of WEEE. It can be used to represent the space interference relationship between components of the WEEE.

- Phase 2 is to obtain all the feasible disassembly sequences with the developed matrix analysis algorithm.

The details of each phase are explained below.

3.1.1 Phase 1 – Space Interference Matrix

Firstly, based on a CAD model of WEEE, row-major 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 the waste product:

$$\begin{matrix} & C_1 & C_2 & \dots & C_n \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & & \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & & r_{nn} \end{bmatrix} \end{matrix} \quad (1)$$

In the matrix, the element C_i in each row and column denotes one of the components in the product. The element r_{ij} represents the space interference relationship between components i (to be removed component) and j (interfering component) in six directions (X^+ , X^- , Y^+ , Y^- , Z^+ , Z^-) in the 3D environment. If space interference exists between components i and j in one direction, the element r_{ij} in the matrix corresponding to this specific direction is set “1”. Otherwise, it is “0”.

An example is used here to explain the space interference relationship between “A” and “B” components (shown in **Figure 3**). As the component “B” is in the X^+ direction of the component “A”, and “A” is in the X^- direction of “B”, the element r_{AB} in the X^+ direction matrix is therefore “1”, and the element r_{BA} in the X^- direction matrix is “1”. All the other elements are “0”.

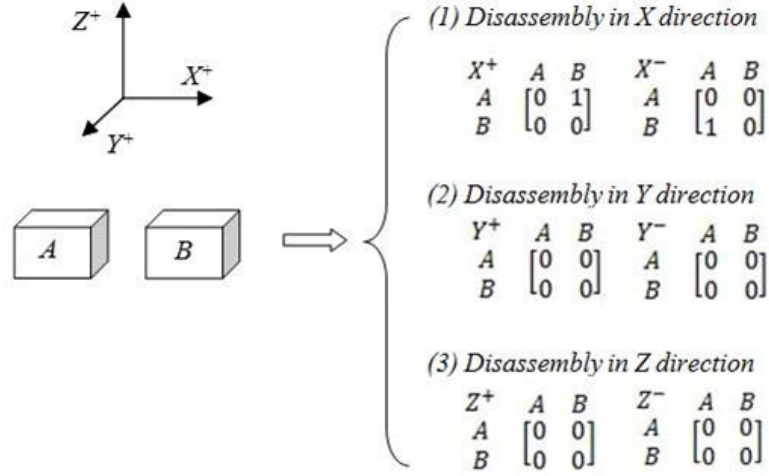


Figure 3 Matrices in six directions to represent the space interference relationships

A four-component product (shown in Figure 4) will be used as an example to explain the matrix analysis method (Phase 2). The space interference matrices are first obtained as given in equations (2-7).

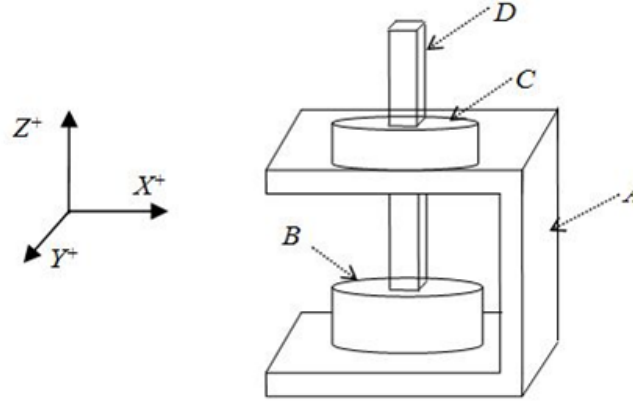


Figure 4 Product with four components

$$S_{X^+} = \begin{matrix} & \begin{matrix} A & B & C & D \end{matrix} \\ \begin{matrix} A \\ B \\ C \\ D \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{matrix} \quad (2)$$

$$S_{X^-} = \begin{matrix} & \begin{matrix} A & B & C & D \end{matrix} \\ \begin{matrix} A \\ B \\ C \\ D \end{matrix} & \begin{bmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \end{matrix} \quad (3)$$

$$\begin{array}{c}
A \quad B \quad C \quad D \\
S_{y^+} = \begin{array}{l} A \\ B \\ C \\ D \end{array} \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}
\end{array} \quad (4)$$

$$\begin{array}{c}
A \quad B \quad C \quad D \\
S_{y^-} = \begin{array}{l} A \\ B \\ C \\ D \end{array} \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}
\end{array} \quad (5)$$

$$\begin{array}{c}
A \quad B \quad C \quad D \\
S_{z^+} = \begin{array}{l} A \\ B \\ C \\ D \end{array} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\end{array} \quad (6)$$

$$\begin{array}{c}
A \quad B \quad C \quad D \\
S_{z^-} = \begin{array}{l} A \\ B \\ C \\ D \end{array} \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\end{array} \quad (7)$$

3.1.2 Phase 2 – Matrix Analysis Algorithm

Based on the obtained space interference matrices in six directions, a matrix analysis algorithm is then developed to obtain all the feasible disassembly sequences of the product. The aforementioned example is used here to explain the details of the developed matrix analysis algorithm. Firstly, equation (8) is generated by combining equations (2-7) in six directions:

$$\begin{array}{c}
A \quad B \quad C \quad D \\
S = \begin{array}{l} A \\ B \\ C \\ D \end{array} \begin{bmatrix} 000000 & 010011 & 000010 & 111100 \\ 100011 & 000000 & 000010 & 111100 \\ 000001 & 000001 & 000000 & 111100 \\ 111100 & 111100 & 111100 & 000000 \end{bmatrix}
\end{array} \quad (8)$$

The Boolean operator “OR” is used here for the above equation for each component in the row direction. For instance, in a row, if there is any “1” in a direction, the final result in that direction after the “OR” operation will be “1”. Otherwise, the final result in the direction will be “0”. Equation (9) is obtained below:

$$\begin{array}{c}
A \quad B \quad C \quad D \quad \text{Result} \\
S = \begin{array}{l} A \\ B \\ C \\ D \end{array} = \begin{bmatrix} 000000 & 010011 & 000010 & 111100 \\ 100011 & 000000 & 000010 & 111100 \\ 000001 & 000001 & 000000 & 111100 \\ 111100 & 111100 & 111100 & 000000 \end{bmatrix} \begin{array}{l} 111111 \\ 111111 \\ 111101 \\ 111100 \end{array}
\end{array} \quad (9)$$

The result “111111” represents the relationship between one component and all the other remaining components of the product in six directions. 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 **Figure 5** can be used to explain the concept. In equation (9), components “A” and “B” could not be disassembled in any direction as the results are all “1”; component “C” can be disassembled in Z^+ direction as the result is “0” in this direction; component “D” can be disassembled in Z^+ and Z^- directions.

Boolean operator ‘OR’ in rows
 \Downarrow

$$\begin{array}{c}
\begin{array}{l} A \\ B \\ C \\ D \end{array} = \begin{array}{l} A \\ B \\ C \\ D \end{array} = \begin{bmatrix} 000000 & 010011 & 000010 & 111100 \\ 100011 & 000000 & 000010 & 111100 \\ 000001 & 000001 & 000000 & 111100 \\ 111100 & 111100 & 111100 & 000000 \end{bmatrix} \begin{array}{l} 111111 \\ 111111 \\ 111101 \\ 111100 \end{array}
\end{array}$$

\Rightarrow ‘A’ could not be disassembled
 \Rightarrow ‘B’ could not be disassembled
 \Rightarrow ‘C’ could be disassembled in Z^+
 \Rightarrow ‘D’ could be disassembled in $Z^+ Z^-$

$\underbrace{\hspace{10em}}$
 Direction: $X^+ X^- Y^+ Y^- Z^+ Z^-$

Figure 5 Feasible disassembly sequence analysis for the product

If component “D” is disassembled in the Z^+ direction firstly, the remaining combined space interference matrix is updated as shown below:

$$\begin{array}{c}
A \quad B \quad C \quad \text{Result} \\
S = \begin{array}{l} A \\ B \\ C \end{array} = \begin{bmatrix} 000000 & 010011 & 000010 \\ 100011 & 000000 & 000010 \\ 000001 & 000001 & 000000 \end{bmatrix} \begin{array}{l} 010011 \\ 100011 \\ 000001 \end{array}
\end{array} \quad (10)$$

From equation (10), components “A” and “B” can be disassembled in three directions, and the component “C” can be disassembled in five directions. If component “C” is disassembled in the Z^+ direction, then the remaining combined space interference matrix is shown below:

$$S = \begin{matrix} & \begin{matrix} A & B \end{matrix} \\ \begin{matrix} A \\ B \end{matrix} & \begin{bmatrix} 000000 & 010011 \\ 100011 & 000000 \end{bmatrix} \end{matrix} \quad \begin{matrix} Result \\ 010011 \\ 100011 \end{matrix} \quad (11)$$

From equation (11), components “A” and “B” can be disassembled in three directions. After “B” is disassembled in the Y^+ direction, the product has been disassembled completely. Loop the above analysis process until all the feasible disassembly sequences of the product are obtained. Based on the above analysis, the total feasible disassembly sequences for the product is 192 (30+30+30+30+30+30+6+6) (shown in **Figure 6**).

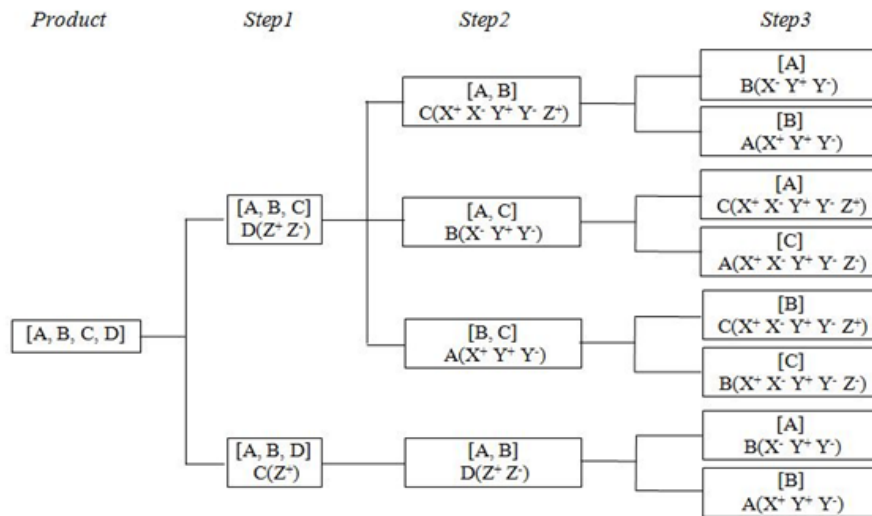


Figure 6 All feasible disassembly sequences for the product

The obtained all feasible disassembly sequences with geometrical constraints are then evaluated based on the evaluation and decision-making method to get the optimised selective disassembly sequence of a product within an acceptable time. Details on the evaluation and decision-making method are explained in the next section.

3.2 An Evaluation and Decision-making Method

According to the WEEE/RoHS Directives, the restricted recycling rate of WEEE is required to be met, 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, disassembly factories would also improve the disassembly profit by prioritising heavy and valued components during disassembly. Based on the above scenario, an evaluation and decision-making method is developed to selectively disassemble WEEE to meet the above requirements. It is composed by three steps: (1) to calculate the profit of the disassembly operation, (2) to identify hazardous, heavy and high-value components, and (3) to calculate the recycling rate of WEEE. Meanwhile, the developed methods are incorporated with a brute-force search method [28] to find out the optimised sequence to meet the economic and environmental requirements, including: (1) to remove all hazardousness, high-value and heavy components from WEEE before shredding and disposal, (2) to meet the restricted recycling rate of the WEEE Directive, and (3) to maximise the disassembly profit.

3.2.1 Profit Calculation of Disassembly Operation

The profit of disassembly operation changes with the different EoL treatments of WEEE. Generally, there are five EoL options available for WEEE, as described in the **Table 2** [22-23].

Table 2 Definitions of the five EoL Types [22-23]

<i>EoL Types</i>	<i>Characters</i>
Type 1 – Reuse	Reuse is that a disassembled component can be reused in the second hand trading for product without any physical or chemical change.
Type 2 – Repair	Repair is when a disassembled component needs be repaired before being reused in the product.
Type 3 - Remanufacture	Remanufacture is to remanufacture a new component by using the materials of a disassembled component from a product.
Type 4 – Recycling	Recycling is to reduce the material size to facilitate sorting and the shredded

	material is separated and recycled with magnetic, air and eddy current separation.
Type 5 – Disposal	Disposal is to landfill or incinerate the product or component.

The profit of the i th disassembly operation ($Profit(Oper_i)$) can be computed as below:

$$Profit(Oper_i) = V(Oper_i) - C(Oper_i) \quad (12)$$

Where $V(Oper_i)$ and $C(Oper_i)$ are the residual value from the disassembled component and cost of the i th disassembly operation, respectively. They can be calculated as follows:

(1) The residual value of the disassembled component of the i th disassembly operation ($V(Oper_i)$)

- If the disassembled component is recycled in Type 1 or Type 2, $V(Oper_i)$ is calculated with the residual value of component in the second hand trading market.
- If the disassembled component is recycled in Type 3 or Type 4, $V(Oper_i)$ is calculated with the residual value of materials of the component.
- If the disassembled component belongs to Type 5, $V(Oper_i)$ is zero as no material is recycled from the component.

Equation (13) is used to explain the above concept:

$$\begin{cases} V(Oper_i) = V(Component_i) & \text{if } Comp_i = \text{Type 1 or Type 2} \\ V(Oper_i) = V(\sum_{j=1}^n (w_{ji} \times r_{ji}^{cyc})) & \text{if } Comp_i = \text{Type 3 or Type 4} \\ V(Oper_i) = 0 & \text{if } Comp_i = \text{Type 5} \end{cases} \quad (13)$$

Where $Comp_i$ represent the i th disassembled component, w_{ji} and r_{ji}^{cyc} represent the weight and recycling rate of the j th material in the i th component respectively.

(2) The cost of the i th disassembly operation ($C(Oper_i)$)

The result of $C(Oper_i)$ varies with the different EoL Types. It can be computed as below:

$$\begin{cases} C(Oper_i) = C^{disassembly}(Oper_i) + C^{clean}(Oper_i) & \text{if } Comp_i = \text{Type 1} \\ C(Oper_i) = C^{disassembly}(Oper_i) + C^{repair}(Oper_i) & \text{if } Comp_i = \text{Type 2} \\ C(Oper_i) = C^{disassembly}(Oper_i) & \text{if } Comp_i = \text{Type 3} \\ C(Oper_i) = C^{shredding}(Oper_i) + C^{dseparation}(Oper_i) & \text{if } Comp_i = \text{Type 4} \\ C(Oper_i) = W_i \times C^{landfill/incinerate}(Oper_i) & \text{if } Comp_i = \text{Type 5} \end{cases} \quad (14)$$

Where W_i is the weight of the disassembled component; $C^{disassembly}(Oper_i)$, $C^{clean}(Oper_i)$, $C^{repair}(Oper_i)$, $C^{shredding}(Oper_i)$, $C^{separation}(Oper_i)$ and $C^{landfill/incinerate}(Oper_i)$ represent the cost of disassembly, cleaning, repair, shredding, separation, landfill and incineration of the i th component respectively. They can be calculated based on the time spent on the disassembly operation ($T^{disassembly}(Oper_i)$), the wage of labor (W^{labor}), the expense of factory ($E^{factory}$) per day (indirect cost) and the number of workers in each factory (N^{labor}). For instance, $C^{disassembly}(Oper_i)$ can be computed in equations (15-17) as follows:

$$C^{disassembly}(Oper_i) = C^{labor}(Oper_i) + C^{factory}(Oper_i) \quad (15)$$

$$C^{labor}(Oper_i) = T^{disassembly}(Oper_i) \times W^{labor} \quad (16)$$

$$C^{factory}(Oper_i) = T^{disassembly}(Oper_i) \times E^{factory} / N^{labor} \quad (17)$$

Based on the above analysis, Total Profit (TP) of a product after the disassembly operation can be computed as below:

$$TP = \sum_{i=1}^n Profit(Oper_i) \quad (18)$$

3.2.2 Identification of Hazardous, Heavy and High-value Components of WEEE

(1) Hazardous components

According to the Environment law, all the components containing hazardous materials need to be taken apart from WEEE for further recycling and processing. The hazardous

components of WEEE could be identified with the RoHS Directive in Europe [24] and the Code of Federal Regulations in USA with Title 40: Protection of Environment [25].

- ***The RoHS Directive*** restricts the following six substances: (1) Lead, (2) Mercury, (3) Cadmium, (4) Hexavalent chromium, (5) Polybrominated biphenyls, and (6) Polybrominated diphenyl ether. The maximum permitted concentrations in non-exempt products are 0.1% or 1000 ppm (except for cadmium, which is limited to 0.01% or 100 ppm) by weight.
- ***The Code of Federal Regulations with Title 40: Protection of Environment*** identifies the hazardousness by calculating the component that contains any of the contaminants listed in Table 3 at the concentration equal to or greater than the respective value given in this table.

Table 3 Maximum concentration of contaminants for the toxicity characteristic [25]

<i>Contaminant</i>	<i>Regulatory Level (mg/L)</i>	<i>Contaminant</i>	<i>Regulatory Level (mg/L)</i>
Arsenic	5.0	Hexachlorobenzene	30.13
Barium	100.0	Hexachlorobutadiene	0.5
Benzene	0.5	Hexachloroethane	3.0
Cadmium	1.0	Lead	5.0
Carbon tetrachloride	0.5	Lindane	0.4
Chlordane	0.03	Mercury	0.2
Chlorobenzene	100.0	Methoxychlor	10.0
Chloroform	6.0	Methyl ethyl ketone	200.0
Chromium	5.0	Nitrobenzene	2.0
o-Cresol	4200.0	Pentachlorophenol	100.0
m-Cresol	4200.0	Pyridine	35.0
p-Cresol	4200.0	Selenium	1.0
Cresol	4200.0	Silver	5.0
2,4-D	10.0	Tetrachloroethyl-ene	0.7
1,4-Dichlorobenzene	7.5	Toxaphene	0.5
1,2-Dichloroethane	0.5	Trichloroethyl-ene	0.5
1,1-Dichloroethylene	0.7	2,4,5-Trichlorophenol	400.0
2,4-Dinitrotoluene	30.13	2,4,6-Trichlorophenol	2.0
Endrin	0.02	2,4,5-TP (Silvex)	1.0
Heptachlor (and its epoxide)	0.008	Vinyl chloride	0.2

Here, equation (19) is used to identify the hazardous components ($C^{hazardous}$) of WEEE as below:

$$Comp_i = C^{hazardous} \quad \text{if } Comp_i(Material_j) \geq Restricted(Material_j) \quad (19)$$

Some major hazardous components of WEEE are also listed in **Table 4** [26], among them, printed circuit boards and liquid crystal display screen are hazardous components in LCD-TVs.

Table 4 Major hazardous components of WEEE [26]

<i>Components</i>	<i>Characters</i>
Cathode ray tubes (CRTs)	Fluorescent coating covers the inside of panel glass and lead in the cone glass
Printed circuit boards	Cadmium in certain components, such as SMD chip resistors, infrared detectors and semiconductors
Liquid crystal displays	LCD screens greater than 100cm ² have to be removed from WEEE
Gas discharge lamps	Mercury has to be removed
Component containing mercury such as switches and thermostats	Mercury is used in some thermostats, sensors, relays and switches
Component containing chlorofluorocarbon (CFC), Hydrochlorofluorocarbons (HCFCs) and Hydrofluorocarbons (HFCs)	CFCs, HCFCs and HFCs present in the foam and the refrigerating circuit must be properly extracted and destroyed

(2) Heavy and high-value components

The heavy components (C^{heavy}) and high-value components ($C^{high-value}$) can be identified as below:

$$Comp_i = C^{hazardous} \quad \text{if } W(Comp_i) \geq Set(weight\ of\ Comp_i) \quad (20)$$

$$Comp_i = C^{high-value} \quad \text{if } V(Comp_i) \geq Set(value\ of\ Comp_i) \quad (21)$$

If the weight/value of the disassembled component is greater than the setting weight/value by the customer, the component is identified as heavy/high-value component.

3.2.3 Recycling Rate of WEEE

The recycling rate ($R_{recycling}$) is defined in below:

$$R_{recycling} = \frac{\sum_{j=1}^N \sum_{i=1}^j (w_{ji} \times r_{ji}^{cyc})}{W_{total}} \times 100\% \quad (22)$$

Where, W_{total} is the total weight of a waste product, w_{ji} and r_{ji}^{cyc} are the weight and recycling rate of its j th material of the i th component, respectively. **Table 5** shows the recycling rate of different materials [18-19]. The restricted recycling rate changes with different categories of the WEEE Directive. **Table 6** shows the 10 different categories of the WEEE Directive [27]. **Table 7** shows the minimum targets applicable for different categories in the WEEE directive [27].

Table 5 A part of recycling rate of product materials [18-19]

Material name	Recycling Rate	Recovering rate	Material name	Recycling rate	Recovering rate
ABS	74	90	PS	62	90
PC	0	90	PVC	0	90
PC/ABS	0	90	Steel	91	91
PMMA	0	90	Aluminum	91	91
PET	90	91	Copper	85	85
PP	90	91	Iron	94	94

Notes: if component is comprised of a single material, all values are set as 100%

Table 6 Categories in the WEEE Directive [27]

1. Large household appliances	6. Electrical and electronic tools
2. Small household appliances	7. Toys, leisure and sports equipment
3. IT and telecommunications equipment	8. Medical devices
4. Consumer equipment	9. Monitoring and control instruments
5. Lighting equipment	10. Automatic dispensers

Table 7 The recycling rates for different categories [27]

Categories	1, 10	3, 4	2, 5, 6, 7, 8, 9
Recycling (%)	80	75	70

For instance, LCD-TVs belong to Category 4 “Consumer equipment”, and the restricted recycling rate of LCD-TVs is 75% which can be obtained in the **Table 7**. Meanwhile, the recycling rate of LCD-TVs can be calculated based on the mass of each material in components and the related recycling rate shown in the **Table 5**.

3.2.4 Objective Function of the Selective Disassembly Optimisation

Based on the evaluation and decision making method, the choice of a selective disassembly plan is then converted into a constrained optimisation problem. The constraints are represented in equations (23)-(26) and the objective function is represented in equation (27).

- 1) Remove all the hazardous, high-value and heavy components

$$Remove(\sum_{r=1}^m C_r^{hazardous}) \quad (23)$$

$$Remove(\sum_{s=1}^p C_s^{high-value}) \quad (24)$$

$$Remove(\sum_{t=1}^q C_t^{heavy}) \quad (25)$$

- 2) Meet the restricted recycling rate of the WEEE Directive

$$\sum_{i=1}^n R_{recycling}(Oper_i) \geq WEEE\ Directive(R_{recycling}) \quad (26)$$

- 3) Maximise the disassembly profit

$$Maximise(TP = \sum_{i=1}^n Profit(Oper_i)) \quad (27)$$

A software package was developed in Java language to obtain the feasible solution space as described in the section 3.1 and to incorporate the decision making method for WEEE. In order to validate the effectiveness of the proposed methods (focus of this paper) quickly, a brute-force search method [28] is employed initially to find out the optimised selective disassembly sequence from the feasible solution space. Although the search time of the brute-

force method for LCD-TVs is affordable, when the number of components in the space interference matrices increases, the search time increases exponentially, and therefore a more efficient optimisation method that can handle products with much more components is desirable. Further research on the aspect is ongoing.

4. INDUSTRIAL CASES STUDY ON CHANGHONG LCD-TVs

The LCD-TVs studied here are produced by the Changhong Electronics Company, Ltd. from China, which is the biggest television producer in China. The company provides information about LCD-TVs of the type of LC24F4, such as the bill of materials, exploded view, mass of each component and the detailed assembly processes. The structure of the LCD-TV is shown in **Figure 7(a)** and **(b)**. The exploded view of a LCD-TV is shown in **Figure 7(c)**. As shown in **Figure 7(d)**, a LCD-TV is typically assembled by three main parts: (1) base assembly part, (2) front cover assembly part, and (3) back cover assembly part.

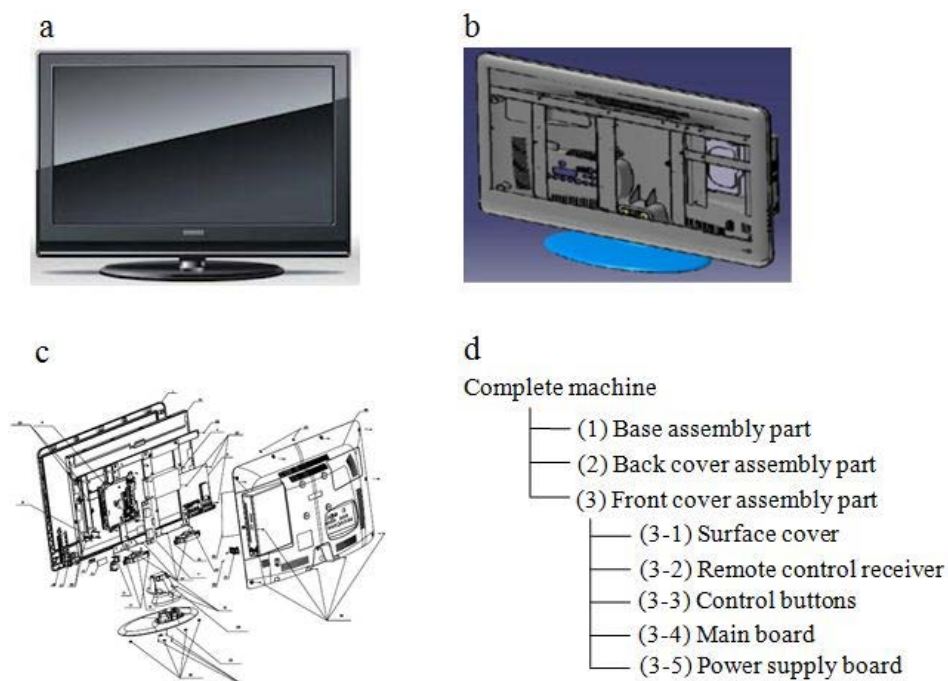


Figure 7 The LCD-TVs and its structures (a) LCD-TV; (b) LCD-TV CAD model; (c) exploded view of LCD-TV structure and (d) parts of LCD-TV

	A	B	C	D	E	F	G	H	I		A	B	C	D	E	F	G	H	I				
$S_{X^+} =$	A	[	0	0	0	0	0	0	1	1	1	A	[	0	0	0	0	0	1	1	1		
	B		0	0	0	0	0	0	1	1	1		B		0	0	0	0	0	1	1	1	
	C		0	0	0	0	0	0	1	1	1		C		0	0	0	0	0	1	1	1	
	D		0	0	0	0	1	1	0	0	0		D		0	0	0	0	1	1	0	0	0
	E		0	0	0	1	0	1	0	0	0	$S_{X^-} =$	E		0	0	0	1	0	1	0	0	0
	F		0	0	0	1	1	0	1	1	1		F		0	0	0	1	1	0	1	1	1
	G		1	1	1	0	0	0	0	1	0		G		1	1	1	0	0	0	0	1	0
	H		1	1	1	0	0	0	1	0	1		H		1	1	1	0	0	0	1	0	1
	I		0	0	0	0	0	0	0	1	0		I		0	0	0	0	0	0	0	1	0
]]								

$$S_{Y^+} = \begin{matrix} & A & B & C & D & E & F & G & H & I \\ \begin{matrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Y^-} = \begin{matrix} & A & B & C & D & E & F & G & H & I \\ \begin{matrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Z^+} = \begin{matrix} & A & B & C & D & E & F & G & H & I \\ \begin{matrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{matrix} & \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Z^-} = \begin{matrix} & A & B & C & D & E & F & G & H & I \\ \begin{matrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

The space interference matrices for X+, X-, Y+, Y- directions here are the same, as the base assembly part is a concentric structure along the Z direction so that a component cannot be removed in any direction along the XOY plane if it is surrounded by another component on the same plane. After combining the above six matrices and using Boolean operator “OR” in rows, the obtained result is as follows:

$$S = \begin{matrix} & A & B & C & D & E & F & G & H & I & \text{Result} \\ \begin{matrix} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \end{matrix} & \begin{bmatrix} 000000 & 000010 & 000010 & 000010 & 000010 & 000010 & 111110 & 111110 & 111100 \\ 000001 & 000000 & 000010 & 000010 & 000010 & 000010 & 111110 & 111110 & 111100 \\ 000001 & 000001 & 000000 & 000010 & 000010 & 000010 & 111110 & 111110 & 111100 \\ 000001 & 000001 & 000001 & 000000 & 111101 & 111101 & 111101 & 111101 & 000000 \\ 000001 & 000001 & 000001 & 111110 & 000000 & 111101 & 000001 & 000001 & 000000 \\ 000001 & 000001 & 000001 & 111110 & 111110 & 000000 & 111110 & 111110 & 111100 \\ 111101 & 111101 & 111101 & 000010 & 000010 & 000010 & 000000 & 111101 & 000001 \\ 111101 & 111101 & 111101 & 000010 & 000010 & 000010 & 111110 & 000000 & 111100 \\ 000000 & 000000 & 000000 & 000000 & 000000 & 000000 & 000010 & 111100 & 000000 \end{bmatrix} \end{matrix}$$

Based on the developed matrix analysis algorithm in Section 3.1.2, there are totally 918 feasible disassembly sequences for the base assembly part.

4.1.2 Front Cover Assembly Part

The front cover assembly part of the LC24F4 LCD-TV is shown in **Figure 9**. 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.

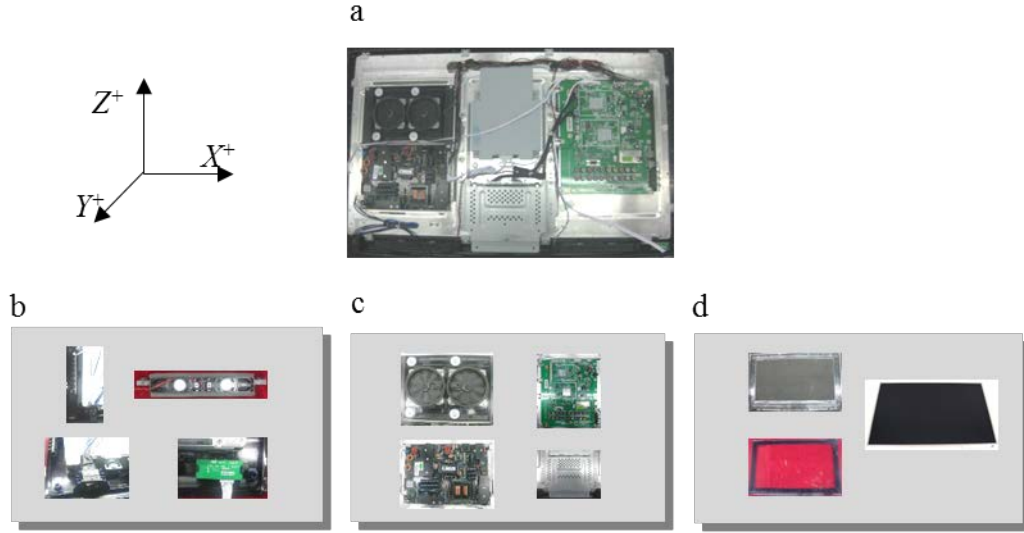


Figure 9 The front assembly part of the LC24F4 LCD-TV: (a) front assembly part, (b) components J, K, L, M, (c) components N, O, P, Q, and (d) components R, S, T

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

$$S_{x^+} = \begin{matrix} & \begin{matrix} J & K & L & M & N & O & P & Q & R & S & T \end{matrix} \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{x^-} = \begin{matrix} & \begin{matrix} J & K & L & M & N & O & P & Q & R & S & T \end{matrix} \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Y'} = \begin{matrix} & J & K & L & M & N & O & P & Q & R & S & T \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Y'} = \begin{matrix} & J & K & L & M & N & O & P & Q & R & S & T \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Z'} = \begin{matrix} & J & K & L & M & N & O & P & Q & R & S & T \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{Z'} = \begin{matrix} & J & K & L & M & N & O & P & Q & R & S & T \\ \begin{matrix} J \\ K \\ L \\ M \\ N \\ O \\ P \\ Q \\ R \\ S \\ T \end{matrix} & \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \end{matrix}$$

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

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

Based on the developed matrix analysis algorithm, there are a total of 7,096,320 feasible disassembly sequences for the front assembly part.

4.1.3 Back Cover Assembly Part

The back cover assembly part of the LC24F4 LCD-TV is composed of three parts: (U) back cover, (V) cover plate, and (W) support (shown in **Figure 10**)

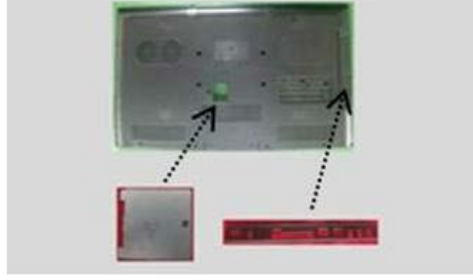
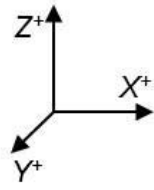


Figure 10 The back cover assembly part of LCD-TV

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

$$S_{x^+} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{matrix} \quad S_{x^-} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$S_{y^+} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{matrix} \quad S_{y^-} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$S_{z^+} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{matrix} \quad S_{z^-} = \begin{matrix} & U & V & W \\ \begin{matrix} U \\ V \\ W \end{matrix} & \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{matrix}$$

The combined matrix can be obtained as follows:

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

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

Based on the above analysis, the number of all the feasible disassembly sequences with geometric constraints of the LC24F4 LCD-TV is $2.6058e^{+10}=918 \times 7096320 \times 4$ (base assembly part \times front cover assembly part \times back over assembly part). Compared with the theoretical full search space, which could be as large as $23!=23 \times 22 \times \dots \times 2 \times 1 = 2.5852e^{+22}$, the search range for a disassembly planning algorithm to find the optimised disassembly sequence is reduced by $9.9209e^{+11}$ times (shown in **Table 8**). It is obvious that the developed feasible solution space method can dramatically reduce the search range and obtain all the feasible disassembly sequences of the LC24F4 LCD-TV to alleviate the computational effort on the search of the optimal disassembly sequence.

Table 8 Comparison between our developed method and full disassembly solution space

This developed method: (all feasible disassembly sequences)	$918 \times 7096320 \times 4 = 2.6058e^{+10}$
Full search space: (all disassembly sequences)	$23! = 23 \times 22 \times \dots \times 2 \times 1 = 2.5852e^{+22}$
Search range reduction:	$2.5852e^{+22} / 2.6058e^{+10} = 9.9209e^{+11}$ times

4.2 Evaluation and Decision-making on LCD-TVs

The components and some properties of the LC24F4 LCD-TVs provided by Changhong Electronics Company, Ltd. are listed in **Table 9**. The total mass of a LC24F4 LCD-TV is 5648.2 grams. Among the component/material composition, the PCBs, which are mainly the main board and power supply board, loudspeaker, and LCD screen are quite complex and are composed of several different materials. Other components of LCD-TVs are usually made by a single material such as: Steel, Aluminum, Copper, ABS, etc.

Table 9 Components and some properties of the LC24F4 LCD-TVs

<i>Assembly part</i>	<i>Components</i>	<i>Mass (g)</i>	<i>Materials</i>
Base assembly part	(A) metal fixing plate	15.0	Aluminium
	(B) metal washer 1	10.0	Steel
	(C) metal washer 2	10.0	Steel
	(D) top metal support	25.0	Aluminium
	(E) cylindrical support 1	30.0	PS
	(F) cylindrical support 2	20.0	PS
	(G) toughened glass seat	150.0	Glass

Front assembly part	(H) steel plate	50.0	Steel
	(I) rubber gasket	20.0	Black plastic
	(J) control button	9.2	ABS
	(K) power switch	5.0	TPE, Copper
	(L) side loudspeaker	152.0	Steel, Copper, Plastic, etc...
	(M) control receiver board	3.0	Copper, FP4
	(N) positive loudspeaker	77.8	Steel, Copper, Plastic, etc...
	(O) power supply board	118.0	Copper, Gold, Lead, Cadmium, etc...
	(P) main board	196.0	Copper, Gold, Lead, Cadmium, etc...
	(Q) metal board	183.0	Steel
	(R) metal mounting plate	639.0	Steel
	(S) surface frame	270.8	ABS
	(T) LCD screen	2900.0	Silicon, Glass, Polymer, Mercury, etc...
Back cover assembly part	(U) back cover	723.8	PS
	(V) cover plate	25.0	PET
	(W) support	15.6	ABS

The calculation of disassembly time, value, cost of the disassembly operations, and the identification of hazardous, heavy and high-value components of the LC24F4 LCD-TVs are described in the following. The results of the calculations are listed in **Table 10**.

- **Disassembly time:** firstly, the base assembly part, front assembly part and back cover assembly part are disassembled manually to calculate the disassembly time of each component.
- **Disassembly cost:** the disassembly cost can be calculated in equations (15-17). The cost of labour and factory operation are set as 150 Yuan/day and 3000 Yuan/day separately, there are 100 workers in the disassembly factory.
- **Residual value:** the residual value can be calculated in equation (13). All the potential values are calculated based on the values of materials of components as there is no component that can be reused and repaired in the LC24F4 LCD-TVs.
- **Hazardous components:** the hazardous components can be identified in equation (19). In the LC24F4 LCD-TVs, (O) Power supply board, (P) Main board, and (T) LCD screen are identified as hazardous as discussed in Section 3.2.2 and they have to be removed for further recycling and processing.

- **Heavy components:** the heavy components can be identified in equation (20). If the component weight is over 2.5% ($141.205\text{g} = 5648.2 \times 2.5\%$ g) of the whole mass of LC24F4 LCD-TVs, the component is identified as heavy component by the disassembly factory. Components, (G) toughened glass seat, (L) side loudspeaker, (P) main board, (Q) metal board, (R) metal mounting plate, (S) surface frame, (T) LCD screen, and (U) back cover, are identified as heavy components.
- **High-value components:** the high-value components can be identified by equation (21). If the potential value of a component is over 5% ($1.1403 \text{ Yuan} = 22.8054 \times 5\%$ Yuan) of the whole residual value of LC24F4 LCD-TV, the component is identified as a high-value component by the disassembly factory. Here, components, (Q) metal board, (R) metal mounting plate, (T) LCD screen, (U) back cover, are identified as high-value components.

Table 10 The results of the calculations for hazardous, heavy and high-value components

<i>Components</i>	<i>Disassembly Time (minute)</i>	<i>Disassembly Cost (Yuan)</i>	<i>Residual Value(Yuan)</i>	<i>Hazardous</i>	<i>Heavy</i>	<i>High - Value</i>
(A) metal fixing plate	0.30	0.1125	0.2970			
(B) metal washer 1	0.04	0.0150	0.0660			
(C) metal washer 2	0.04	0.0150	0.0660			
(D) top metal support	0.35	0.1313	0.4950			
(E) cylindrical support 1	0.10	0.0376	0.2400			
(F) cylindrical support 2	0.10	0.0376	0.1600			
(G) toughened glass seat	0.23	0.0863	0.2380		○	
(H) steel plate	0.20	0.0751	0.3300			
(I) rubber gasket	0.10	0.0376	0.0200			
(J) control button	0.08	0.0300	0.0100			
(K) power switch	0.08	0.0300	0.0100			
(L) side loudspeaker	0.35	0.1313	0.6000		○	
(M) control receiver board	0.10	0.0376	0.4000			
(N) positive loudspeaker	0.25	0.0940	0.3071			
(O) power supply board	0.70	0.2626	0.6466	○		
(P) main board	0.70	0.2626	0.7908	○	○	
(Q) metal board	0.59	0.2213	1.2078		○	○
(R) metal mounting plate	1.82	0.6826	4.2174		○	○
(S) surface frame	1.23	0.4613	1.1000		○	
(T) LCD screen	1.42	0.4438	9.6684	○	○	○
(U) back cover	1.65	0.5326	1.7904		○	○
(V) cover plate	0.03	0.0113	0.2280			
(W) support	0.04	0.0150	0.0169			

For the base assembly part, only component (Ⓔ - toughened glass seat) is required to be removed. Based on the obtained feasible solution space for the base assembly part in the previous section, **Figure 11** shows the developed software and the obtained optimised sequence (Ⓐ Ⓑ Ⓒ Ⓓ Ⓔ) with the maximum profit to dismantle component (Ⓔ) based on computing. The optimised selective disassembly sequences for the front assembly part and back cover assembly part are also obtained using the developed software. **Table 11** shows the obtained result and the related disassembly cost.

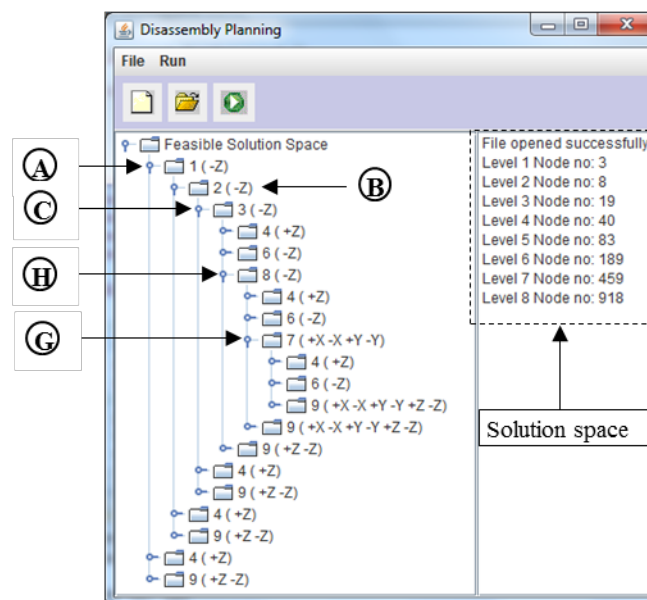


Figure 11 The developed software and the obtained optimised sequence

Table 11 The obtained optimal disassembly sequences for LCD-TVs

Sub assembly	Selective disassembly sequence	Disassembly cost (Yuan)
Base assembly part	Ⓐ Ⓑ Ⓒ Ⓓ Ⓔ	0.3049
Front assembly part	⒱ ⒴	0.5439
Back cover assembly part	Ⓐ Ⓑ Ⓒ Ⓓ Ⓔ	2.5971

An EoL process flow is then generated with the obtained optimal selective disassembly sequence for the LC24F4 LCD-TV (Shown in **Figure 12**). If the disassembled component is composed of a single material, the EoL process of the component is Type 3 (remanufacture) as there is no reuse and repair components in the LC24F4 LCD-TV, and the recycling rate of the material is 100% (except glass is 80%); if the disassembled component is composed of several materials, the EoL process of the component is Type 4 (shredding), and the recycling rate of the material is different based on different separation methods. After the EoL disassembly process, the remaining components are recycled for valuable materials with EoL shredding process. In the end, all the worthless materials and components are disposed with landfill and incineration processes.

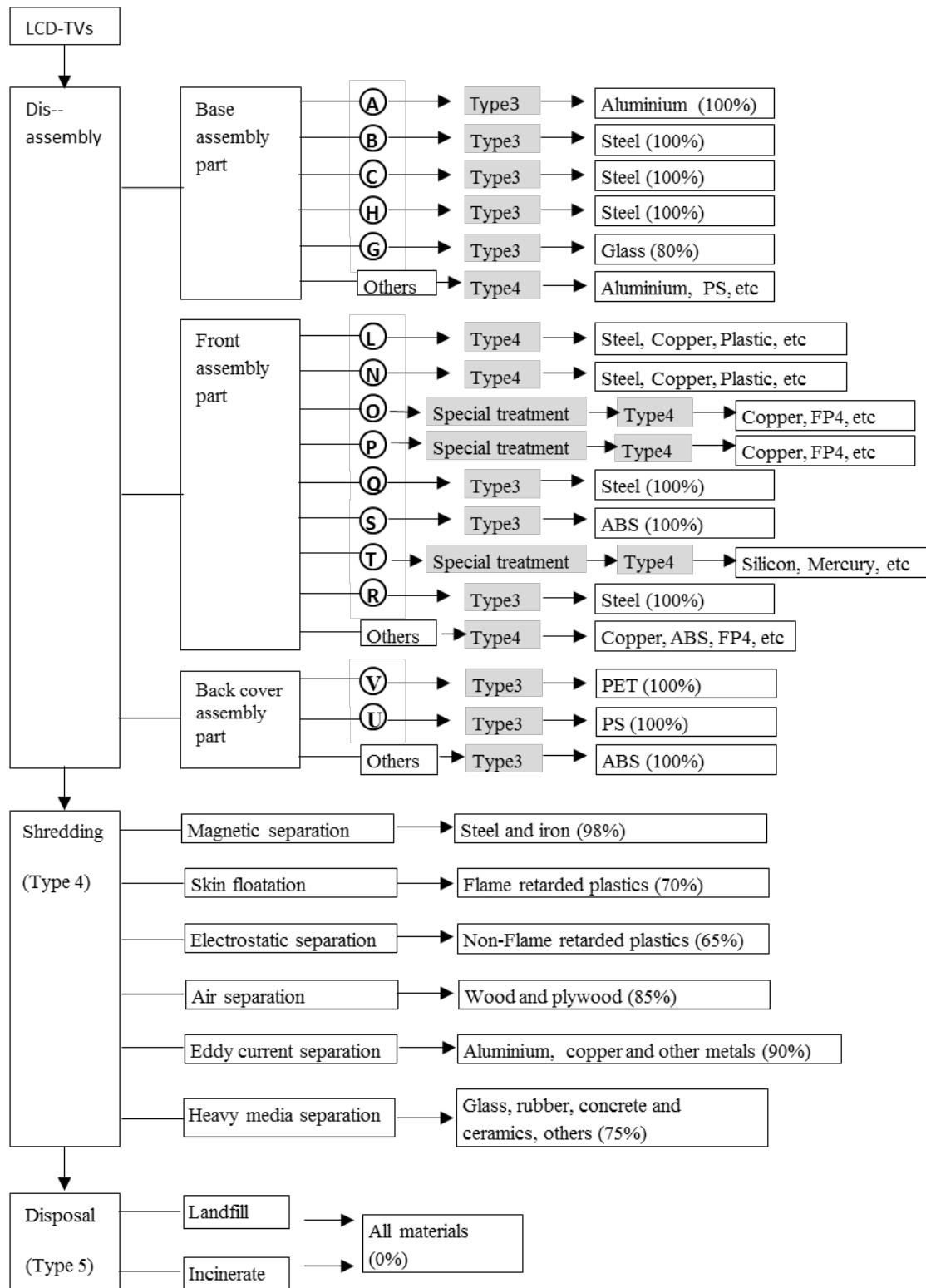


Figure 12 The EoL process flow for the LC24F4 LCD-TV

Based on the above analysis, the recycling rate and the total disassembly profit of the LC24F4 LCD-TV can be calculated in the following. The results are listed in **Table 12**.

- **The recycling rate:** based on the mass and recycling rate of different materials/components, the weights of recycled materials of each component can be calculated, and the recycling rate of the LC24F4 LCD-TV is 86.55% ($86.55\% = 4888.93/5648.2 \times 100\%$).
- **The total disassembly profit:** the total disassembly cost can be calculated in equation (14). The costs of labour and factory operation are set as 150yuan/day and 450yuan/day separately. There are 10 workers in each cleaning, repair, shredding, separation, landfill and incineration factories. The total disassembly profit is 12.9616 Yuan ($12.9616 = 22.9054 - 9.9438$).

Table 12 The recycling rate and profit of the LC24F4 LCD-TV

<i>Components</i>	<i>Mass (g)</i>	<i>Efficiency (%)</i>	<i>Material recycled (g)</i>	<i>Value (Yuan)</i>	<i>Total cost (Yuan)</i>	<i>Profit (Yuan)</i>
(A) metal fixing plate	15.0	100	15.0	0.2970	0.1125	0.1845
(B) metal washer 1	10.0	100	10.0	0.0660	0.0150	0.0510
(C) metal washer 2	10.0	100	10.0	0.0660	0.0150	0.0510
(D) top metal support	25.0	90	22.5	0.4950	0.0394	0.4556
(E) cylindrical support 1	30.0	70	21.0	0.2400	0.0113	0.2287
(F) cylindrical support 2	20.0	70	14.0	0.1600	0.0113	0.1487
(G) toughened glass seat	150.0	80	120.0	0.2380	0.0863	0.1517
(H) steel plate	50.0	100	50.0	0.3300	0.0751	0.2549
(I) rubber gasket	20.0	70	14.0	0.0200	0.0113	0.0087
(J) control button	9.2	65	5.98	0.0100	0.0090	0.0010
(K) power switch	5.0	65	3.25	0.0100	0.0090	0.0010
(L) side loudspeaker	152.0	75	114	0.6000	0.1707	0.4293
(M) control receiver board	3.0	80	2.4	0.4000	0.0436	0.3564
(N) positive loudspeaker	77.8	75	58.4	0.3071	0.1222	0.1849
(O) power supply board	118.0	80	94.4	0.6466	0.4986	0.1480
(P) main board	196.0	80	156.8	0.7908	0.6546	0.1362
(Q) metal board	183.0	100	183.0	1.2078	0.2213	0.9865

(R) metal mounting plate	639.0	100	639.0	4.2174	0.6826	3.5348
(S) surface frame	270.8	100	270.8	1.1000	0.4613	0.6387
(T) LCD screen	2900.0	80	2320	9.6684	6.2438	3.4246
(U) back cover	723.8	100	723.8	1.7904	0.5326	1.2578
(V) cover plate	25.0	100	25.0	0.2280	0.0113	0.2167
(W) support	15.6	100	15.6	0.0169	0.0150	0.0019
Total	5648.2	86.55	4888.93	22.9054	9.9438	12.9616
Total recycling material:			4888.93	Total profit:		12.9616
Recycling rate (86.55%) ≥WEEE Directive (75%)						

After the above process, the disassembly results of the LC24F4 LCD-TV are achieved as follows:

- 1) All the hazardous, heavy and high-value components are removed, including
 - Hazardous components, (O) power supply board, (P) main board, and (T) LCD screen.
 - Heavy components, (G) toughened glass seat, (L) side loudspeaker, (P) main board, (Q) metal board, (R) metal mounting plate, (S) surface frame, (T) LCD screen, and (U) back cover.
 - High-value components, (Q) metal board, (R) metal mounting plate, (T) LCD screen, (U) back cover.
- 2) The recycling rate meets the restricted recycling rate of the WEEE Directive
The recycling rate is 86.55%, which is greater than the restricted recycling rate 75% of the WEEE Directive.
- 3) The optimised selective disassembly sequence has been obtained with the maximum profit of the disassembly operation.

5. CONCLUSION

In this paper, a systematic selective disassembly approach is developed to handle WEEE to meet the environmental and economic requirements. The characteristics and contributions of the research include:

- Space interference matrix is used to represent the space interference relationship of components in six directions of WEEE. In this manner, all the space interference relationship between components can be digitally recorded and analysed in the next step;
- A matrix analysis algorithm is developed to obtain all the feasible disassembly sequences by analysing six space interference matrices in a 3D environment. It is capable of obtaining all the feasible disassembly sequences of WEEE, and the result can be used as a solution space to search for an optimised disassembly sequence within an acceptable runtime;
- An evaluation and decision-making method is developed to find out the optimised selective disassembly. It is capable of removing all hazardous, high-value and heavy components from WEEE, maximising disassembly profit and meeting the restricted recycling rate of the WEEE Directive;
- An industrial case study on LC24F4 LCD-TVs has been used to demonstrate the performance of the developed approach.

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APPENDIX

Notation

$C^{clean}(Oper_i)$	clean operation cost
$C^{disassembly}(Oper_i)$	disassembly operation cost
$C^{hazardous}$	hazardous components
C^{heavy}	heavy components
$C^{high-value}$	high-value components
C_i	component element in matrix
$C^{landfill/incinerate}(Oper_i)$	disposal operation cost
$C(Oper_i)$	operation cost
$Comp_i$	components
$C^{repair}(Oper_i)$	repair operation cost
$C^{shredding}(Oper_i)$	shredding operation cost
$C^{separation}(Oper_i)$	separation operation cost
$E^{factory}$	factory expense
N^{labor}	worker number
$Profit(Oper_i)$	operation profit
r_{ij}	space interference relationship
r_{ji}^{cyc}	recycling rate of the material
$R_{recycling}$	recycling rate
$T^{disassembly}(Oper_i)$	disassembly operation time
TP	total profit
$V(Oper_i)$	operation value
w_{ji}	recycling weight of the material
W^{labor}	worker wage
W_{total}	total weight