Chapter 2
A Distributed Service of Selective Disassembly Planning for Waste Electrical and Electronic Equipment with Case Studies on Liquid Crystal Display

Weidong Li, K. Xia, B. Lu, K. M. Chao, L. Gao and J. X. Yang

Abstract Waste Electrical and Electronic Equipment (WEEE) are one of the most significant waste streams in modern societies. In the past decade, disassembly of WEEE to support remanufacturing and recycling has been growingly adopted by industries. With the increasing customization and diversity of Electrical and Electronic Equipment (EEE) and more complex assembly processes, 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 legislative and economic considerations of specific stakeholders, is becoming an important yet still challenging research topic in recent years. In this chapter, a Particle Swarm Optimization (PSO)-based selective disassembly planning method embedded with customizable decision-making models and a novel generic constraint handling algorithm has been developed. With multi-criteria decision

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making models, the developed method is flexible to handle WEEE to meet the various requirements of stakeholders. Based on the generic constraint handling and intelligent optimization algorithms, the research is capable to process complex constraints and achieve optimized selective plans. Practical cases on Liquid Crystal Display (LCD) televisions have been used to verify and demonstrate the effectiveness of the research in different application scenarios. A distributed environment to deploy the service for remote access and control has been designed to support collaborative work.

2.1 Introduction

The mounting demand for new products has brought more production activities worldwide in recent years. This rapid development, however, has been hindered by the increasing concerns on the scarcity of natural resources and environmental issues. Statistics show that from 1985 the resource consumption on the global level has been higher than the ecological capability of the Earth. 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 [1]. 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), are becoming one of the major and challenging waste streams in terms of quantity and toxicity. For instance, there are approximately 7 million tons of WEEE generated in Europe per year [2]. In China, 1.1 million tons of WEEE are generated per year [3]. Due to the rapid technical innovations and shorter usage lifecycle of EEE, WEEE are growing much faster than any other municipal waste streams. To keep the Earth cleaner, End-of-Life (EoL) recovery strategies are critical to shape the future of WEEE lifecycle management patterns. Among the strategies, remanufacturing is viewed as a "hidden green giant" and attracting escalating attentions of researchers and practitioners [4–7]. Remanufacturers seek to bring some components of products after their services back into 'as new' condition by carrying out necessary disassembly, overhaul, and/or repairing operations for re-use to extend lifecycles. 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 regulation bodies with an aim to make products and components after services more recyclable, reusable and remanufacturable (i.e., reducing the waste arising from WEEE, improving and maximizing recycling, reuse and other forms of recovery of waste from WEEE, and minimizing the impact on the environment from their treatment and disposal);

- According to the WEEE Directives, a producer (manufacturer, brand owner or importer)'s responsibility is extended to the post-consumer stage of WEEE, instead of stopping at selling and maintenance (i.e., Extended Producer Responsibility—EPR [8, 9]. 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 USA to ensure Original Equipment Manufacturers (OEMs) and suppliers to provide free access to remanufacturing information facilities in global chains [10];
- Good remanufacturing planning and management can effectively balance economic and environmental targets, and bridge 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 numbers of successful cases in industries, including single use cameras (Eastman Kodak and Fuji Film), 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, ReCelluar—USA, Greener solution—UK).

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 different decision-making models according to the perspectives and criteria of stakeholders [11]. 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 [12–17]. 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 [5, 18, 19];

- Disassembly planning and operation sequencing. Typical disassembly operations based on manual, semi-automatic and automatic processes and the associated tool-kits were summarized [5]. 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 [11, 20–22]. 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* [5, 23, 24].

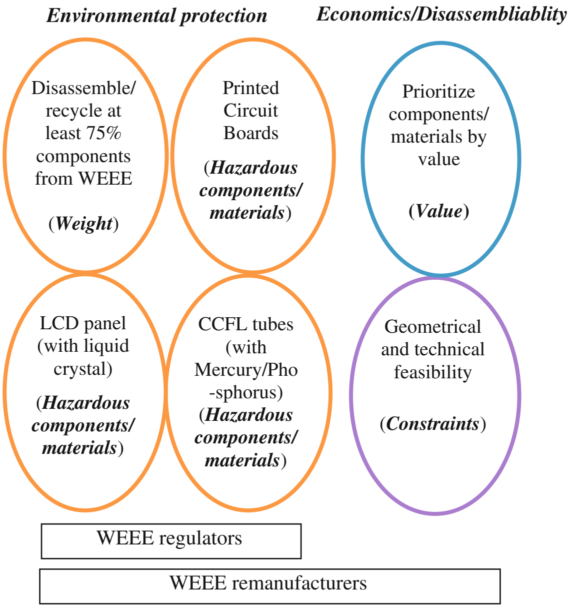
Attributing to booming personalized and mass-customized EEE, it is still challenging to apply the developed methods to the increasingly diversified and personalized WEEE to make sensible decisions and meet different stakeholders' perspectives. In this chapter, a Particle Swarm Optimization (PSO)-based selective disassembly planning method with customizable decision making models and a novel constraint handling algorithm has been developed. The method is adaptive to various types of WEEE, flexible for customized decision modeling and making for different stakeholders, and capable for handling complex constraints and achieving optimized solutions during disassembly planning. Industrial cases on Liquid Crystal Display (LCD) televisions have been used to verify and demonstrate the effectiveness of the developed method in different application scenarios.

2.2 Selective Disassembly Planning Approach

2.2.1 Customizable Decision-Making Modeling for Selective Disassembly Planning

Disassembly of WEEE involves different stakeholders, such as environmental regulators and remanufacturers, which will lead 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. 2.1, an example of LCD WEEE is used to illustrate the above scenario.

Fig. 2.1 Criteria for different decision-making models



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.

2.2.1.1 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, which is a part of the above complete operations. The number of the selected operations is m, and the *ith* operation is denoted as $Oper(i)$. *DP* can be represented as:

$$DP = \bigcup_{i=1}^{m} (Oper(i), Position(Oper(i))) \tag{2.1}$$

where $\bigcup$ 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* $(Index\_H)$

Hazardousness of the *ith* 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:

$$Index\_H = \sum_{i=1}^{m} (H(Oper(i)) * Position(Oper(i))) \tag{2.2}$$

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 in earlier positions in *DP* to achieve a smaller *Index_H*.

For instance, the hazardousness of $Oper(1), Oper(2), Oper(3), Oper(4)$ are (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 re-arranged 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 *ith* 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 re-usable 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:

$$Index\_V = \sum_{i=1}^{m} ((V(Oper(i))/T(Oper(i)) * Position(Oper(i))) \tag{2.3}$$

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 *ith* 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:

$$Index\_W = \sum_{i=1}^{m} (W(Oper(i)) * Position(Oper(i))) \tag{2.4}$$

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.

2.2.1.2 Disassembly Constraints

During the process of disassembly, there are some geometrical or technical constraints to specify precedent relationships between disassembly operations. Three examples in Fig. 2.2 are used to illustrate the concept. In (a) and (b), there are two disassembly directions for Components A and B respectively. Due to the geometrical blocking relationship, the first disassembly operation (denoted as $Oper(1)$) is to disassemble the joining mechanism associated with Component B and Housing, and the second disassembly operation ($Oper(2)$) is to dismantle the joining mechanism between Components A and B. Therefore, $Oper(1)$ is constrained to be prior to $Oper(2)$ geometrically. In (c), there is a single disassembly direction for Components A and B. Geometrically, it can dismantle either the joining mechanism between Component B and Housing first ($Oper(1)$), or the

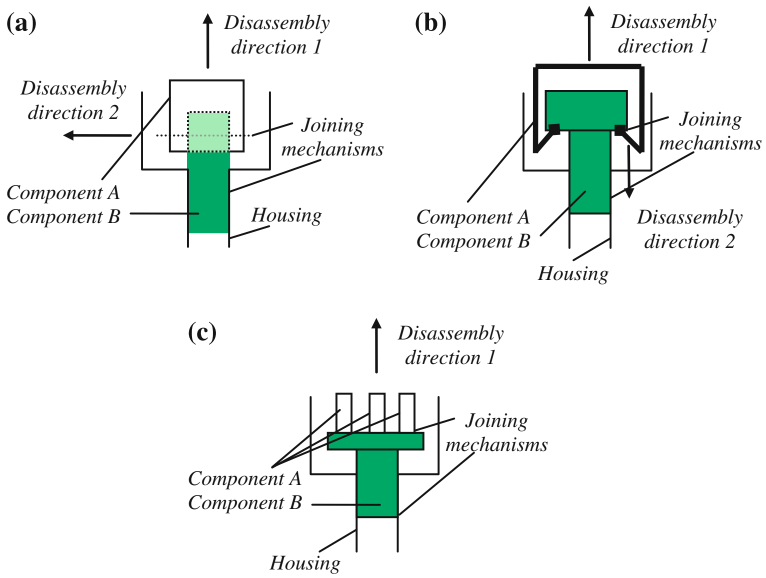


Fig. 2.2 Examples of constraints during disassembly **a** A geometrical constraint. **b** A geometrical constraint. **c** Technical constraint

joining mechanism between Components A and B first (*Oper*(2)) first. However, from the technical point of view, it is recommended to remove the joining mechanism between Component B and House 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.

2.2.1.3 Decision-Making Objective

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

$$\begin{aligned} &Mimimise(Index\_H, Index\_V, Index\_W) \\ &= Minimise\left(w_1^* Index\_H + w_2^* Index\_V + w_3^* Index\_W\right) \end{aligned} \tag{2.5}$$

where $w_1 - w_3$ are the weights. Different weights can be set by different users to reflect varied priorities of the three indices. A higher weight means more attentions will be paid to that index, and a zero value means such 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 normalization process is illustrated in case studies.

2.2.2 A Generic Constraint Handling Algorithm

There could be a number of precedence constraints between the disassembly operations for a set of WEEE. Under the situation, it is usually difficult to generate a valid disassembly plan. In order to address complex constraints in WEEE disassembly dynamically and adaptively, a new constraint handling algorithm, which employs a generic process to handle various constraints, has been developed. The manipulation operations of the algorithm, which are based on data structure and double-linked list design, can ensure that all the constraints in a disassembly plan will be met during the process of selection and optimization process (such selection and optimization process will be explained in Sect. 2.2.3). The workflow of the algorithm is described in Fig. 2.3. In the process, there are several important symbols to be highlighted below.

m	The number of the selective disassembly operations for a set of WEEE
m_1	The number of the disassembly operations without any constraints
$m - m\_1$	The number of the disassembly operations with constraints
LL	A double linked list for the disassembly operations with constraints
LL_1	A double linked list to store immediate results during the algorithm manipulation
Current operation	The working operation during the manipulation of the algorithm

2.2.3 An 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. More details of GA and SA implementation can refer to [25, 26].

A classic PSO algorithm was inspired by the social behavior of bird flocking and fish schooling [27]. Three aspects will be considered simultaneously when an individual fish or bird (particle) makes a decision about where to move: (1) its current

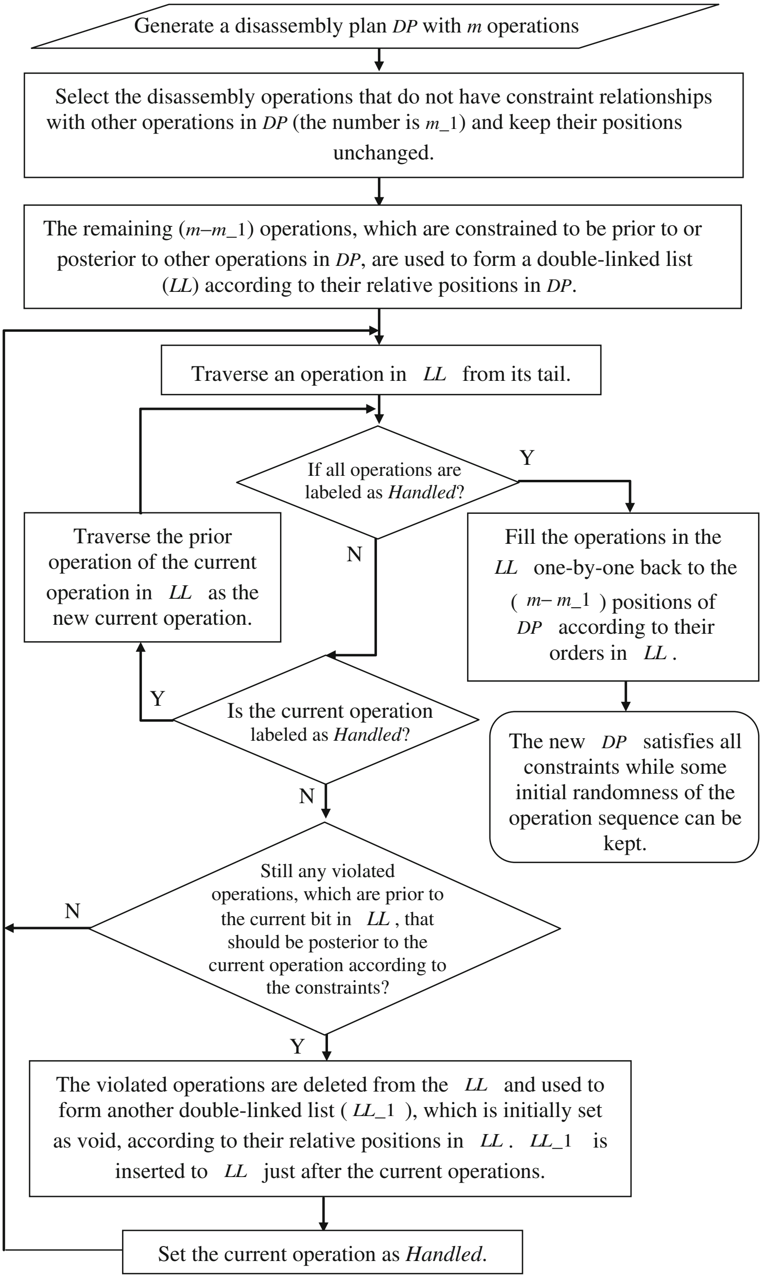


Fig. 2.3 The workflow of the generic constraint handling algorithm

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 its neighbor 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. 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 (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 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 re-organized to form Child 1. The positions and velocities of the left part of Parent 2 and the right part of Parent 1 are re-organized to form Child 2;
- Shift. This operator is used to exchange the positions and velocities of two operations in a particle 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.

2.3 Case Studies for Selective Disassembly Planning

2.3.1 Background

Televisions can be generally classified into six groups: Cathode Ray Tube (CRT), LCD, Plasma Display Panel (PDP), Light Emitting Diode (LED), Rear Projection (RP) and Digital Light Projection (DLP). The LCD televisions have been developed quickly over the past decades and they are now the market leader sharing the biggest market (e.g., the global market figures for the LCD televisions are forecasted to surpass $80 Billion in 2012 [24]). A 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. The LCD televisions 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 televisions of the type of LC24F4, such as the Bill of Materials (BoMs), exploded view, mass of each parts and the detailed assembly processes. The structure of the LCD television is shown in Fig. 2.4a and b. The typical exploded view of a LCD television is shown in (c). As shown in (d), a LCD television is typically assembled by three main parts: front cover assembly part, back cover assembly part and base assembly part. Among them, the front cover assembly part is composed of a surface frame, a remote control receiver board, a control button board, a main board, a power supply board, a Low-Noise Block (LNB) converter board (optional), and a DVD ROM (optional). The mass of the LC24F4 LCD television is 5963.8 g, and the main component/material composition is shown in Fig. 2.5, in which the percentage is represented in terms of the ratio of Mass. Among the component/material composition, the Printed Circuit Boards (PCBs, which are mainly main boards and power supply boards) and LCD screens are quite complex in terms of structure and recycling. Other components/ materials include cables, wires, pins, switches and rubbers. The cables, wires, pins

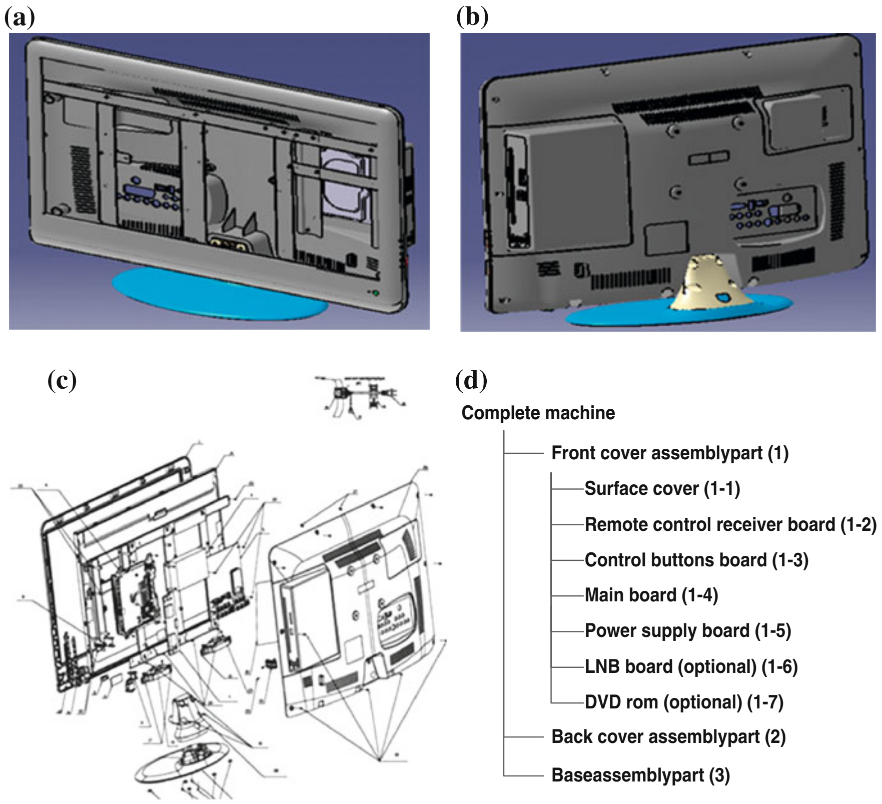
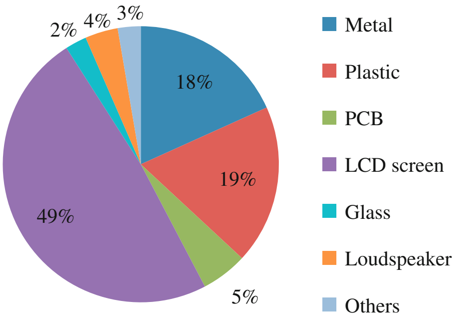


Fig. 2.4 A LCD television and its structure views. **a** Front view of the LCD television. **b** Back view of the LCD television. **c** Exploded view of the LCD television. **d** Part of the BoMs of the LCD television

Fig. 2.5 The component/material composition of the LCD television



and switches consist of plastics that are usually Polyvinyl Chloride (PVC), non-ferrous mainly Copper and Aluminum. Current EoL disposal for LCD televisions is typically landfill or incineration, and this form of disposal restricts the ability to recover potentially reusable materials from waste LCD television, e.g., components to be reused or remanufactured, and recycled materials like Steel, Aluminum, Copper, etc. Due to the increasingly significant market share of LCD televisions, it is imperative to apply effective methods to plan the disassembly of LCD televisions.

As discussed earlier, in the disassembly planning process of LCD televisions, it needs to address environmental, economic and feasibility issues. Environmental regulators need to ensure that specific targets with regard to the remanufacturing and recycling of LCD televisions are adhered to, and remanufacturers expect to isolate components that can generate higher potential re-use values from the overall assembly in a timely and efficient manner to ensure that labor overheads are maintained as low as possible [24].

The hazardous materials contain substances that are harmful to humans or directly harmful to the environment. Some hazardous materials are parts of LCD televisions, such as PCBs, which often contain Tin, Lead, Cadmium and capacitors containing polychlorinated biphenyls, and the LCD screen, which contains fluorescent tubes with Mercury and liquid crystals.

According to the WEEE Directives, components in WEEE with the hazardous materials need to be disassembled and then recycled (e.g., The EU WEEE Directive states that PCBs greater than 10 cm^2 need to be removed from WEEE). It is also required to disassemble at least 75 % components from a set of WEEE. In a LCD television, key components contribute significantly to the overall weight of the LCD so that they should be handled first to improve disassembly efficiency. Meanwhile, another key issue to achieving successful recycling is to ensure that there is an economic gain from the disassembly process.

Based on the BoMs of the LCD television of the type of LC24F4, the process of disassembly can be planed. Figure 2.6 is used to represent the constraints of the disassembly plan and called the disassembly constraint graph. Except the disassembly constraint graph, there are several other methods to represent the disassembly constraints, such as disassembly tree, state diagram and And/or Graph [21]. In the graph, nodes represent operations and connection lines represent the precedence constraint relationships between operations. Meanwhile, each operation is

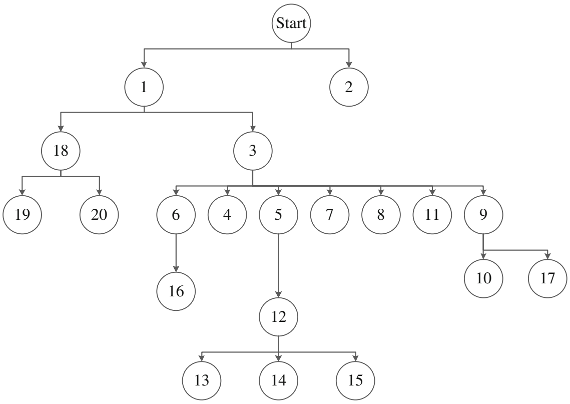


Fig. 2.6 The disassembly constraint graph

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, potential value and hazardousness. Table 2.1 lists the properties of the disassembly process according to the disassembly operation number.

2.3.2 Selective Optimizations and Comparisons

2.3.2.1 An Initial Plan

According to the constraints, different disassembly plans can be created. One of these chosen is (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20). Its physical disassembly process is shown in Fig. 2.7. 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.

2.3.2.2 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 Forumar (2.5) were set 1). The input data is shown in the Table 2.1.

The disassembly planning selection and optimization process is shown in Fig. 2.8a. During the computation process, results were normalised, 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.

The hazardousness removal, weight removal and potential recovery value for the initial plan (shown in the previous Fig. 2.7) 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 was optimized in this selective plan.

In (b) and (c), it can show that the initial plan will take 15 disassembly operations to achieve 100 % hazardousness removal, and also 15 operations for 75 %

Table 2.1 Disassembly operations and some properties of the 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. Disassembly 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
			25.0	0.1520	
		Insulating board	0.5	0.0033	
		M3x8GB/T9074.4	0.6	0.0004	
		M4x8GB/T9074.4			
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	

(continued)

Table 2.1 (continued)

Disassembly operations	Time (s)	Components	Mass (g)	Potential value (Yuan)	Hazardousness removal
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
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
			50.0	0.0640	
		Steel plate	20.0	0.0200	
		Rubber gasket			

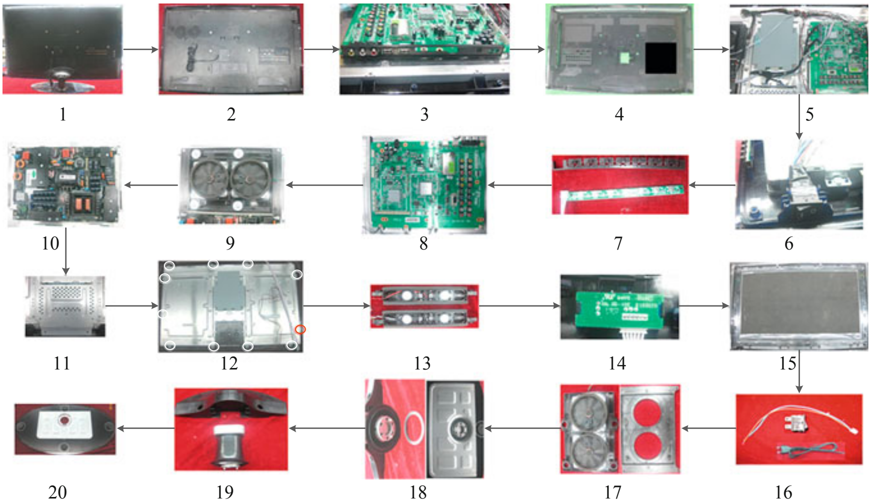


Fig. 2.7 A disassembly plan of the LCD television (an initial plan)

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 were 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.

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 %). 15 % 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.

2.3.2.3 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 (2.5) were set 1

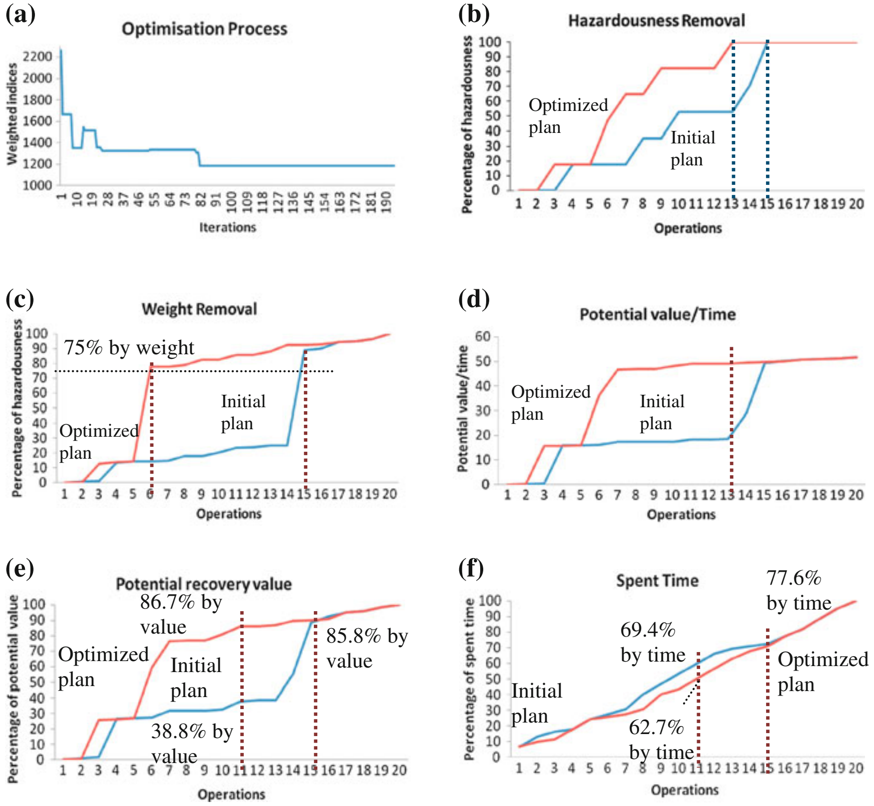


Fig. 2.8 Optimization processes for scenario 1 (all weights are 1) **a** The disassembly planning optimization process. **b** Hazardousness removal during disassembly. **c** Weight removal during disassembly. **d** Potential recovery value/spent time during disassembly. **e** Potential recovery value during disassembly. **f** Spent time during disassembly.

and the weight for Potential Recovery Value 0.5). The input data is shown in the above Table 2.1. The comparison results are shown in Fig. 2.9.

In Fig. 2.9a, 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 7 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 of 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 were set 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

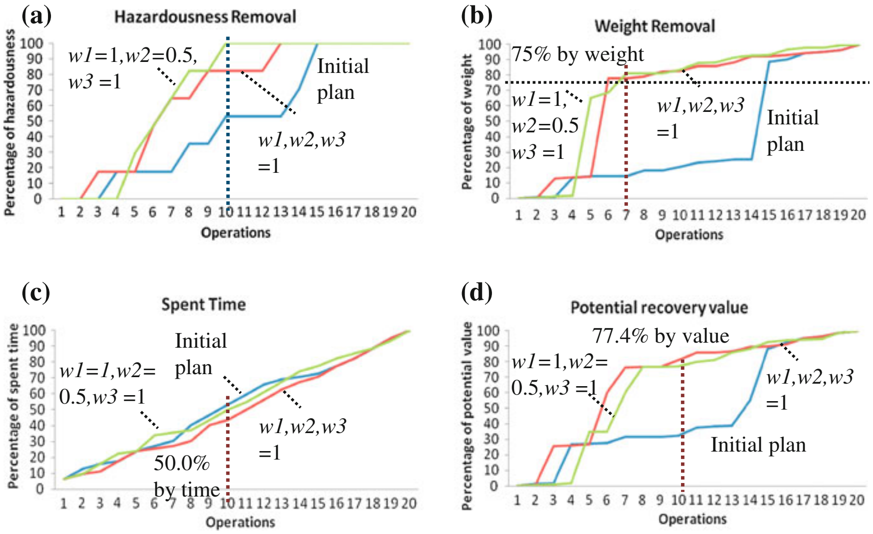


Fig. 2.9 Optimization processes for Scenario 2 (different weights) **a** Hazardousness removal during disassembly. **b** Weight removal during disassembly. **c** Spent time during disassembly **d** Potential recovery value during disassembly

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 %).

2.3.2.4 Environmental Impact Evaluation

Disassembled components can potentially generate values through component re-use/re-manufacturing and material recycling, and they can therefore reduce the environmental impact and climate change effect without the need to make the components from raw materials. The environmental impact and climate change effect of each operation is shown in Table 2.2. The results of the optimized plan under Scenario 1 (all the weights were set as 1) and the initial plan are shown in Fig. 2.10. It can be observed that significant improvements can be made with the optimization process compared to the initial plan (69.4 and 155.3 % improvement in the two aspects).

2.3.2.5 Algorithm Comparisons

Meanwhile, the developed algorithms developed in this research was benchmarked to demonstrate their innovations. The generic constraint handling method in this research was compared with a classic penalty method [28], which is a popular

Table 2.2 The avoided environmental impact/climate change effect of each disassembly operation

Oper(*i*)	Avoided environmental impact (10^{-3} Pt)	Avoided climate change effect (10^{-8} DALY)
1	2.54	1.53
2	13.20	3.37
3	20.12	4.44
4	349.02	57.61
5	349.02	57.61
6	349.02	57.61
7	349.02	57.61
8	351.26	58.96
9	352.75	59.87
10	358.59	62.85
11	496.90	146.47
12	520.17	160.54
13	520.17	160.54
14	520.17	160.54
15	1111.69	465.03
16	1111.69	465.03
17	1184.35	508.96
18	1212.25	525.82
19	1254.89	541.60
20	1292.19	564.15

method applicable to complex constraints. The results are shown in Fig. 2.11a. It can be concluded that the developed generic constraint handling method ensures that the computational process can be conducted in a smoother and more efficient way, and all the generated plans are valid.

The GA, SA and improved PSO algorithms were also used for optimization shown in (b). All of them can yield good results but the SA and the improved PSO both outperform the GA in the case studies, while the improved PSO algorithm is better than the SA. Each iteration of the improved PSO algorithm mainly uses simple mathematical operators that can be finished in a shorter time than those for the GA and the SA algorithms with mainly complex position changing operators so that the improved PSO algorithm is also more efficient to achieve the best value generally.

2.3.3 A Disassembly Planning Service in a Distributed Environment

The developed disassembly planning method will be wrapped as a service in a main framework illustrated in Fig. 2.12. In the framework, apart from the disassembly planning method which dismantles a set of WEEE into the component level, the recycling planning method will be used to support the processing of the disassembled components into materials, and the design for Remanufacturability/

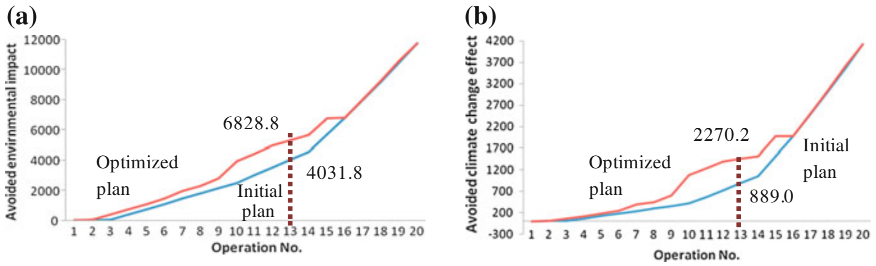


Fig. 2.10 Optimized accumulated avoided environmental impact and climate change effect s **a** Avoided environmental impact. **b** Avoided climate change effect.

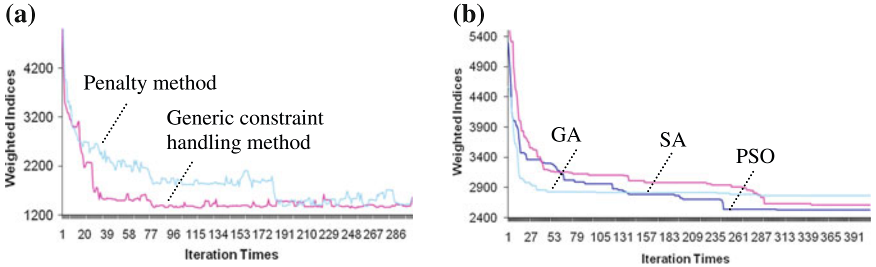


Fig. 2.11 Algorithm comparisons **a** Comparison on constraint handling method. **b** Comparison on intelligent methods

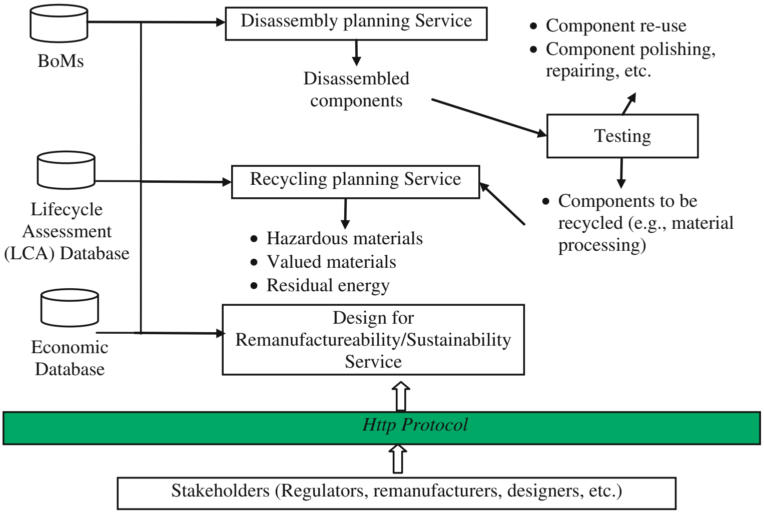


Fig. 2.12 Remanufacturing services and its framework

Sustainability service to support design in a more efficient means. Stakeholders will access the services through the Http protocol remotely.

2.4 Conclusions

WEEE have 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 chapter, an effective selective disassembly planning method has been developed to address the issue systematically. The characteristics and contributions of the research include:

- An improved PSO algorithm-based selective disassembly planning method with customizable decision-making models and a novel constraint handling algorithm has been developed in a systematic means. 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 constraint handling and 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 LCD WEEE have been successfully 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.

In the future, a more intelligent mechanism needs to be developed to generate disassembly constraints from the functions and semantics of the BoMs of EEE automatically and accurately (e.g., not all the assembly constraints will be used to generate disassembly constraints due to the different functions and semantics during EEE assembly and WEEE disassembly). With the mechanism, disassembly plans of WEEE will be generated from the design stage of EEE to support Design for Remanufactureability/Sustainability in a more efficient means.

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