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Generating design alternatives for increasing recyclability of products

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ABSTRACT

This paper proposes a design support method for improving the recyclability of electronic and electrical products. The method estimates the recycling rate of a product based on its end-of-life scenario. The method supports a designer in generating design alternatives that increase the rate by conducting impact analysis with the change of material composition and end-of-life scenario. The method suggests design alternatives with the constraint of keeping the other performance factors (e.g., flexural strength and thermal conductivity) constant by adjusting the geometric parameters (e.g., thickness and volume) of the components.

1. Introduction

The resource circulation of waste electronic and electrical products has become a key environmental issue in manufacturing industry. An effective approach for increasing the recyclability of resources in such products is the application of design for recycling (DfR) [1] at the design stage.

In applying DfR, both the product and its end-of-life (EoL) scenario should be considered since the recyclability of products depends on their EoL treatment processes as well as the composition of the materials. For example, in the current recycling process in Japan [2], a glass panel of an LCD TV is recyclable only if the printed matter on the panel surface is removed and the clean glass cullet is collected.

Although a number of studies have addressed DfR that dealt with the aspect of EoL treatment (e.g., [3–5]), contributions of design changes to the recyclability of a product are not quantified in the conventional DfR methods.

In this paper, we propose a quantitative method for analyzing and modifying product design to improve the recyclability. In this study, recyclability of a product is quantified as 'recyclability rate' defined as the mass fraction of recyclable materials to the total mass of the product [6]. The method generates design alternatives by analyzing the impacts of design changes on the recyclability rate. Here, design changes include those of product design and of EoL scenario. In this direction, Knight and Sodhi analyzed the cost and profit factors in material separation for bulk recycling [7]. Jackson et al. proposed an analytical method for improving environmental factors of products [8].

In general, however, design changes affect various performance factors (e.g., flexural strength and thermal conductivity) other than recyclability. For preventing such side-effects, this method introduces a constraint system for keeping the other performance factors constant by adjusting the geometric features (e.g., thickness and volume) of the components.

The rest of this paper is organized as follows: Section 2 outlines the theory and procedure of the method. Section 3 describes a prototype system based on the proposed method, and Section 4 illustrates the results of a case study on an LCD TV. After the discussion of the case study in Section 5, and Section 6 concludes the paper.

2. Design modification method for improving recyclability

As described in the previous section, the proposed method supports the generation of design alternatives that increase the recyclability rate by conducting impact analysis with the constraint of preventing the side-effects to other performance factors of a product. The method supports a designer in executing DfR at the detailed design stage consisting of the following four steps:

1. The preparation of product model and the description of an EoL scenario
2. The calculation of the recyclability rate
3. Impact analysis on the recyclability rate
4. Generating design alternatives based on the analysis

The following subsections describe every step in detail.

2.1. The preparation of product model and the description of an EoL scenario

This method assumes that a product model and EoL scenario are provided. We represent the product model by a geometric model with bill of material (BOM) data. The BOM includes a list of components and their attributive values, such as materials, mass, and additives (e.g., flame retardants, paints, and stickers). The geometric model of each component corresponds with its attributes in the BOM data.

We represent an EoL scenario by an EoL process flow model [9] and a list of recyclability rates of components and material types.

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The flow model is formalized as a network of EoL treatment processes for a product and its components and materials. The recyclability rates of individual components and material types in a scenario are defined as the ability of the components and the materials to be recycled. Even for the same component, the rate may differ depending on the flow of EoL treatment processes for the component due to the quality of collected material. One of the issues in estimating the recyclability rate at design stage in the current practices is that such difference is often omitted, which results in over-estimation of the recyclability rate. In order to include this aspect into the calculation of the recyclability rate, the method classifies each component of the target product into three 'process-types' based on the criteria for electronic and electrical products defined by IEC TR62635 [6];

Type 1: disassembled and sorted manually into an object that requires selective treatment after sorting, such as smelting and depollution. For example, printed circuit boards and fluorescent tubes are categorized in this type.
Type 2: disassembled and sorted manually into a single material object. For example, the vegetable compartment of a refrigerator, made only of polypropylene, is categorized in this type in the current recycling activities in Japan [2].
Type 3: shredded and sorted by machines and separated into material fragments. Steel from waste electronic and electrical products is categorized in this type in Japan.

In each process-type, if the recyclability rate of a component or material type is zero, this means that the object is not recycled. For example, back cabinet of a LCD TV including flame retardant is not recyclable in EU [11] even if it is disassembled manually. Basically, EoL scenarios are different by regions based on the legislation, policy, recycling technology, recycling cost, and required quality of materials in the region. Therefore, the list of recyclability rates for components and material types also differs depending on scenarios.

2.2. The calculation of recyclability rate

The method calculates the recyclable mass of each component in the product using the following equation.

$$M_k = \sum_i r_i^j m_i \tag{1}$$

where M_k is the recyclable mass of the kth component, M_i is the mass of the ith material in the component, and r_i^j is the recyclability rate of the ith material for process-type j. The r_i^j value is obtained from the list of recyclability rates held in the applied EoL scenario. Let R_{cyc} be the recyclability rate of an entire product defined by the following equation.

$$R_{cyc} = \frac{\sum_k M_k}{M_{Total}} \tag{2}$$

where M_{Total} is the total mass of the product.

2.3. Impact analysis on the recyclability rate

2.3.1. Procedure

As formulated in Eqs. (1) and (2), design parameters affecting the entire recyclability rate of a product are the material, mass, and process-type of each component, and the recyclability rates of the components and materials.

Among the four types of parameters, the change impact of the mass and recyclability rate are smaller than that of the material and process type in most cases according to our survey. Therefore, this paper addresses the design changes on the latter two types of parameters; i.e., changing material and process types.

The change impact of these two types of each component on R_{cyc} is quantified through the impact analysis. For instance, when the process-type of a component is changed from Type 3 to Type 2, the recyclability rates of the materials in the component are changed from r_i^3 to r_i^2 in Eq. (1) and thus R_{cyc} is also changed. The difference of R_{cyc} between Types 3 and 2 is defined as the impact of the change of the process-type.

The impact analysis assesses all combination of components with the changes of the two types, and the results are sorted in order of their impact on R_{cyc}. This impact-order list represents the priority of the design changes for generating design alternatives.

While the process-type is a design parameter of EoL scenarios, material is a parameter of products. Therefore, the material changes affect the physical performance of the product other than recyclability. For example, if the geometry of a component is constant, the material change of the component from steel to polycarbonate may drastically reduce the strength and rigidity to insufficient level. In order to avoid such infeasible design of materials, we introduce a constraint system in the impact analysis, as described in the next subsection.

2.3.2. Constraint for material changes

Materials have their own physical properties such as density, Young's modulus, modulus of elastic, rigidity, rupture, thermal conductivity, and electrical resistivity. Components also have their geometric properties such as volume, surface area, area moment of inertia, and polar moment of inertia. The physical performance of components varies according to the changes of their material and geometric properties.

For the change of materials, the constraint system adjusts geometric parameters of each component so as to maintain the physical performance factors of the component in the current design. This method assumes that the designer has selected important performance factors of each component.

This adjustment mechanism for a component's geometry can be stated as follows:

$$\begin{aligned} &\text{Minimize}: \quad V(\mathbf{G}) \\ &\text{Subject to}: \quad Pf_i(\mathbf{G},\mathbf{M}) \geq Pf_i(\bar{\mathbf{G}},\bar{\mathbf{M}}), \quad i = 0, 1, \ldots, p \end{aligned} \tag{3}$$

where V is the volume of the component, $\mathbf{G}$ is a set of geometric parameters, and $\mathbf{M}$ is a set of material properties. $\bar{\mathbf{G}}$ and $\bar{\mathbf{M}}$ are the geometric parameters and material properties of the current design before the change. Pf_i is a performance factor, and p is the number of the factors selected for the component.

Here, we employ the formulation scheme proposed by Ashby [10] for the concept of the material selection with maintaining the performance factors. They defined the factors by geometric parameters and material properties.

As described in Formula (3), all performance factors must not be smaller than the current design when the material is changed from $\bar{\mathbf{M}}$ to $\mathbf{M}$. Therefore, $\bar{\mathbf{G}}$, $\bar{\mathbf{M}}$ and $\mathbf{M}$ are constant, while $\mathbf{G}$ should be adjusted to minimize the volume of the component.

However, since the geometric parameters of each component have multiple degrees of freedom, the adjustment mechanism in such a large solution space is impossible to formulate. For reducing the solution space, we assume that the boundary of a component moves only to the normal direction of each surface of the component's solid model by the same vertical displacement Δd. For example, imagine the case where a designer selects the bending stiffness of a cylindrical component as the performance factor. Fig. 1 shows the adjustment of the cylinder, where the broken lines represent the displaced surface of the cylinder's

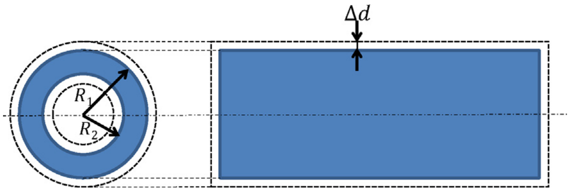

Fig. 1. Example of geometric adjustment.

original geometric model which is denoted as the blue solid body. According to the Ashby's scheme, this performance factor Pf_{bs} can be represented by the following equation.

$$P\,f_{bs} = \frac{EI}{N} \tag{4}$$

where E is the elastic modulus of the constituent material, I is the area moment of inertia at the cross-section plane perpendicular to the axis of the cylinder, and N is the applied bending moment.

The bending stiffness of the component after the material change must not be smaller than the stiffness of the current design. Since the boundary condition N is constant, the geometric property I is the variable that the method can control for maintaining the stiffness. Therefore, I is subject to the following inequality derived from Formulas (3) and (4).

$$I \geq \frac{\bar{E}}{E}\bar{I} \tag{5}$$

where $\bar{E}$ and $\bar{I}$ are the properties of the current design and E is the elastic modulus after the material change.

In the same manner, relationship between material properties and geometric properties are formulated by the constraints of individual performance factors such as rotational stiffness, axial stiffness, yield strength, thermal conductivity, and electrical resistance. Table 1 summarizes the relations of the properties.

In order to satisfy the all constraints selected from this table, the method controls the single parameter Δd of the geometry to adjust I, K, and L in Table 1. In the example of the cylindrical component, I is represented by the following equation.

$$I = \bar{I} + \left(\frac{\partial \bar{I}}{\partial R_1} - \frac{\partial \bar{I}}{\partial R_2}\right)\Delta d \tag{6}$$

where R_1 and R_2 are the external and internal radiuses of the cylinder as shown in Fig. 1. The displacement Δd also changes the volume and mass of the component subordinately.

Consequently, the geometric adjustment defined in Formula (3) achieves Δd that minimizes $V(\mathbf{G})$ and satisfies the all constraints of performance factors selected for the component. The impact of changing material from $\bar{\mathbf{M}}$ to $\mathbf{M}$ on R_{cyc} after the adjustment of Δd is the output of the impact analysis.

Table 1
Constraints on material and geometric properties for individual performance factors.

Performance factor	Constraint	Material property	Geometric property
Rotational stiffness	$K \geq \frac{\bar{E}}{E}\bar{K}$	G	K
Axial stiffness	$I \geq \frac{\bar{E}}{E}\bar{I}$	E	I
Yield strength	$I \geq \frac{\bar{\sigma}}{\sigma}\bar{I}$	σ	I
Thermal conductivity	$L \underset{>}{\leq} \frac{\rho}{\bar{\rho}}\bar{L}$	ρ	L
Electrical resistance	$L \underset{>}{\leq} \frac{\lambda}{\bar{\lambda}}\bar{L}$	λ	L

G, shear modulus; E, Young's modulus; σ, yield point of material; ρ, thermal conductivity of material; λ, volume resistivity; K, polar moment of inertia of area; I, area moment of inertia; L, length between two sides of a solid body.

2.3.3. Deriving candidates for design changes

The impact analysis generates an impact-order list as a priority list of candidates for design changes (i.e., material and process type changes). In the list, the volumes and weights of components before and after the material changes and the geometric adjustment are also listed for supporting the designers in selecting the design candidates.

2.4. Generating design alternatives based on the analysis

Based on the impact analysis, the designer selects some candidates for design changes from the impact-order list. Since the method quantifies the impacts of all design changes of all components, the list may include infeasible candidates. Accordingly, from the highest priority candidate to lower ones in the list, the designer should confirm their feasibility from other aspects than recyclability and select some. For example, the designer should check, e.g., the cost of the new design.

Next, the designer implements the selected candidates. For material changes, the method adjusts the geometry of the component by displacing each surface of the geometric model by Δd. After the adjustment, the designer further modifies the component's geometry to make a valid model from various viewpoints such as manufacturability and connectivity with neighboring components.

When changing the component's process-type, the designer should modify the EoL scenario for the component. If needed, the layout and geometry of the related components are modified to adapt to the new process. For example, Type 2 process requires the component to be disassembled easily.

3. CAD system for generating design alternatives

We developed a prototype system based on LC-CAD [9] that visualizes and manages the product model and the EoL scenario in an integrated manner. The system supports activities including creating a product model, describing an EoL scenario, relating the scenario to the product model, calculating the recyclability rate, assessing the impact of design changes under the geometric adjustment described in Section 2.3.2, and generating design alternatives of the product and its EoL scenario.

For the support of the recyclability rate calculation, the system automatically determines the process-type of each component of a product from the EoL scenario. A recyclability rate database in the system manages the list of recyclability rates for components and material types in each scenario.

4. Case study

We analyzed and modified the design of an LCD TV based on the current EoL scenario for electronic and electrical products in EU as a case study.

First, we described the EoL scenario for the TV. Fig. 2 is the schematic drawing of the EoL process flow in the scenario. Table 2 is a partial list of the recyclability rates of components and material

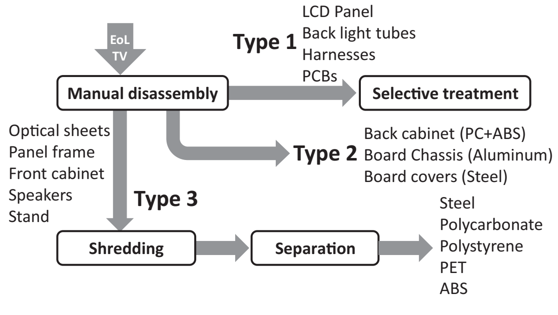

Fig. 2. EoL process flow of LCD TVs in EU.

Table 2
Recyclability rates of components and materials (partial).

Type	Material	r_i^j (%)	Type	Material	r_i^j (%)
1	LCD panel	0	3	ABS	74
	CCFL	80		PC	0
	Cable (high)	33		PC/ABS-FR(40)	0
	Cable (low)	24		PMMA	0
	PCB (high)	18		PET	90
	PCB (low)	14		PP	90
2	PET	94		PS	83
	ABS	94		PVC	0
	PP	94		Steel	94
	PS	100		Aluminum	91
	Aluminum	95		Copper	85
	Copper	95		Iron	70

Table 3
Impact-order list (higher-rank candidates).

Order	Component	Process-type	Material	ΔR_{cyc} (%)	Volume (cm^3)	Weight (kg)
1	Back cabinet	Const.	PC + ABS-FR(40) → steel	22.79	1579.4 → 970.7	1.69 → 7.76
2	Back cabinet	2 → 3	PC + ABS-FR(40) → steel	22.37	1579.4 → 970.7	1.69 → 7.76
3	Back cabinet	Const.	PC + ABS-FR(40) → aluminum	19.53	1579.4 → 1900.0	1.69 → 2.62
4	Back cabinet	2 → 3	PC + ABS-FR(40) → aluminum	18.22	1579.4 → 1900.0	1.69 → 2.62
5	Front frame	3 → 2	Other plastic → steel	8.80	467.3 → 287.2	0.50 → 2.30
6	Front frame	Const.	Other plastic → steel	8.64	467.3 → 287.2	0.50 → 2.30

types. The data in the table were acquired from research reports on the current recycling activities in EU (e.g., [11]).

By disassembling the product and surveying the components, we made a geometric model of the TV with BOM data. Based on the product model and the EoL scenario, we calculated the recyclability rate of the TV and conducted an impact analysis. For the analysis, we selected performance factors to be maintained for each component. For example, yield strength, axial stiffness, and bending strength were selected for the chassis.

Table 3 is the part of the results of the analysis. From this impact-order list, we selected the material change from PC + ABS to steel of back cabinet because the system estimated that the recyclability rate of the TV will improve by 22.79% from the original design as shown in Table 3. On the other hand, this candidate increases the weight of the cabinet from 1.69 kg to 7.76 kg even after the mass reduction by the geometric adjustment. In this case, we prioritized the recyclability and tolerated the gain of the weight.

Then, we selected the material change of front frame from plastics to steel and the process-type change from Type 3 to 2.

For implementing these two design changes, we changed the product design and the EoL scenario, which resulted in a design alternative. The system adjusted the geometric models to adapt to the new materials as described in Section 2.4. Based on the adjusted models, we further modified their geometries. For example, we remove the filets of the back cabinet, because the steel cabinet will be manufactured by stamping process instead of injection for PC + ABS. For the process-type change of the front frame, we changed EoL process flow of the frame in the LC-CAD system. Finally, we confirmed the feasibility of the design alternative on both the product and the EoL process flow models.

5. Discussions

We succeeded in generating a design alternative that improves the recyclability rate of the TV. The system adjusted the geometric model to maintain the physical performances of the original design. Before the adjustment, the weight of the back cabinet was 747.7% of the original model due to the difference of density between PC + ABS and steel under the same volume. But, after the adjustment, the weight became 459.1%. This means that the adjustment mechanism is necessary for analyzing real impact on recyclability and generating feasible design alternatives. In this case, the displacement Δd of the model surface was minus 1.2 mm from the average thickness (3.0 mm) of the original back cabinet model.

In this study, we formalized the five performance factors to be maintained in changing materials as summarized in Table 1. As one of our future works, the method may include other performance factors such as anti-vibration and anti-noise characteristics by formulating the material and geometric parameters. However, because such factors strongly depend on the shape of the component and the geometric relations with the other components, it is difficult to control the performances by the single parameter Δd. In order to tackle this problem, we should extend the adjustment mechanism.

Based on the impact analysis, our method may maximize the recyclability rate of a product by applying optimization schemes to the material and process type selections. However, as described in Section 2.4, design changes should be confirmed from various aspects in each step. Thus, we adopted step-wise manner of generating candidates and selecting some in this study.

6. Conclusion

We proposed a design support method for improving the recyclability of electrical and electronic products. The method quantifies the recyclability of products based on EoL scenarios.

By using the EoL scenario and geometric model of a product, the impact analysis quantifies the effect of design changes, including changes of materials and EoL process types, on the recyclability rates, with the constraint of maintaining other performance factors by adjusting the geometry of the components.

We calculated the recyclability rate of an LCD TV with the EoL scenario in EU as a case study. The impact analysis on the TV suggested feasible design changes such as the material change of back cabinet with the geometric adjustment to maintain the physical performances of the component.

Future work includes applying this geometric adjustment system to analyzing and modifying other DfX such as design for resource and energy efficiency.

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