

NEW METHODOLOGY FOR ENVIRONMENTAL PERFORMANCE EVALUATION OF A PRODUCT'S END-OF-LIFE

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Abstract : End-of-Life Environmental Performance Evaluation System (EoL-EPES) has been developed to enable the systematic assessment of environmental performances of a product's end-of-life. It consists of three indicators including "Eco-Recycling Rate", "Recycling Potential" and "End-of-Life Performance (EoL-performance)". The eco-recycling rate is based on the concept that integrates the cost aspects into the conventional recycling rate and consequently can be used as an indicator representing the degree of economical recycling. The recycling potential which is obtained from 28 criteria evaluation supports designers to recognize the clues for environmental improvements. The EoL-performance defined as a geometric average of the eco-recycling rate and the recycling potential, helps establishing environmental strategies for product improvements. The EoL-EPES has been verified to give an appropriate information on practical environmental evaluation and to facilitate environmental improvements via its application to electronic appliances.

Key Words : disassembly, ecodesign, eco-recycling rate, end-of-life performance, environmental performance, recycling oriented design, recycling potential

INTRODUCTION

Rapid growth of electronic industries has given rise to an increase of electronic wastes, and their treatment or recycling has recently been issued. Disposal of products' wastes containing hazardous substances has also intensively been concerned.

The Commission of the European Communities reported that 6 million tons of waste electrical and electronic equipment (WEEE) were generated on the basis of EU member states in 1998 and the volume of WEEE is expected to have doubled in 12 yr, which is about three

times higher than the growth of the average municipal waste.^{1,2)} The miniaturization and high-integrated function generally may let them have more environmental hazardous potential. For examples, cellular phones and other small electronic devices contain a large number of hazardous substances, such as cadmium and lead, which have long been known to have serious impacts on the environment and public health.³⁾

Many of countries have implemented or have the plans to implement legislations to solve those end-of-life problems on electronic appliances. Extended producer responsibility (EPR) is one of the main terminologies for environmental legislations. The Organization for Economic Cooperation and Development (OECD) defines

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EPR as an environmental policy approach in which a producer's responsibility (physically and/or economically; fully or partially) for a product is extended to the post-consumer stage of a product life cycle.⁴⁾ On the other hand, EPR provides producers incentives depending on their environmental considerations in the design of products. Some of the legislations force producers to take disassembly- and recycling- oriented design into account which can consequently meet the required recycling rate and avoid the use of hazardous substances. In addition to conformance with the legislations, the recycling-oriented design may prevent additional costs for a product's life cycle and get competitive edge.^{5,6)}

Design engineers are thus required to assess the environmental performance of products' end-of-life at the product design stage to identify the improvement potential on their disassembly and recycling aspects.

However, conventional definitions such as recycling rate and recyclability are lacking in representing appropriate end-of-life characteristics of a product and even making misunderstanding because they may be different depending on the conditions of recycling plants.⁷⁾

For these reasons design engineers need supporting methods for the proper evaluation of their proposed design. This paper thus presents the End-of-Life Environmental Performance Evaluation System (EoL-EPES) which represents the end-of-life characteristics properly and makes it easy to identify which components have more improvement potentials.

New environmental performance indicators proposed in this research may give design engineers a guide which can manage the environmental performance of a product's end-of-life at its design phase.

END-OF-LIFE ENVIRONMENTAL PERFORMANCE EVALUATION SYSTEM (EoL-EPES)

The main task of EoL-EPES is to provide a

realistic tool for environmental improvements of products based on quantitative assessment.

The requirements of the indicators to be used for a product's end-of life performance evaluation are:

- to reflect the changes from a product redesign for environmental improvements : Eco-recycling rate
- to identify environmentally weak points and their reasons : Recycling potential
- to provide a reference for the strategy establishment for improvement : End-of-life performance

An indicator satisfying these requirements has not however been reported so far. The set of these three indicators which satisfy the requirements stated above is called "EoL-EPES" in this paper.

The EoL-EPES consists of three sub-elements, i.e., the eco-recycling rate, the recycling potential and the EoL-performance. The eco-recycling rate gives practical expression by means of defining a recycling rate as the product components ratio which can be recycled with no economical losses. The recycling potential provides opportunities which can improve the product's end of life performance based on 28 quantitative criteria concerning product structure, joining techniques and materials. The EoL-performance, defined as a geometric average of the eco-recycling rate and the recycling potential, is to show where the product is positioned at a viewpoint of ecodesign. It can be used as a reference for establishing environmental strategic roadmaps.

To implement the EoL-EPES, a prerequisite information categorized into 3 groups is needed; 'part information', 'connection information' and 'disassembly priority information' (see Table 1).

In addition to the product-related information, a database for the EoL-EPES, including disassembly time for each joining technique, market price for secondary materials and reusable parts, disposal cost for wastes and so on, is required.

Eco-Recycling Rate

Table 1. Prerequisite information for the EoL-EPES

Categories	Contents
Parts Information	part name, shape, size, accessibility, material type, weight, serviceability of parts
Connection Information	types of joining techniques, number of joining techniques, types of disassembly tools
Priority Information	disassembly priority

Conventional indicators for recycling rate are based on only materials' types and their weights.⁸⁾ The material's types and weight are, of course, the factors influencing the product recycling. However these two factors are not sufficient for defining a product's recycling rate appropriately. The recycling rate of a product can be increased by changing not only the weight and types of the materials but also the joining techniques used and the product structure.

In case a product has no hazardous materials which must be removed or pre-treated prior to its recycling and a recycling plant has shredding and sorting facilities without manual disassembly, the two factors, weight and types of materials, may be sufficient for determining the recycling rate of the product. However, most of products contain hazardous materials and recycling plants are mostly implementing both manual disassembly and machine shredding / sorting.

The manual disassembly may cause higher costs due to more manpower and time needed. In addition, the value of recycled materials in the secondhand market influences the recycling rate which recycling plants are trying to achieve in view of the recycling profit.

The recycling rate is thus closely linked to costs. The recycling rate which considers the cost aspects may be even more effective than its conventional definition. Hence, the eco-recycling rate which stands for economical recycling rate is proposed in order to integrate the cost aspects into the conventional recycling rate and consequently to be used as an indicator for recycling-oriented design.

The core concept of the eco-recycling rate is to make use of "segments" which minimize a product's end-of-life cost. It should be noted that the disassembly process is not just the reverse

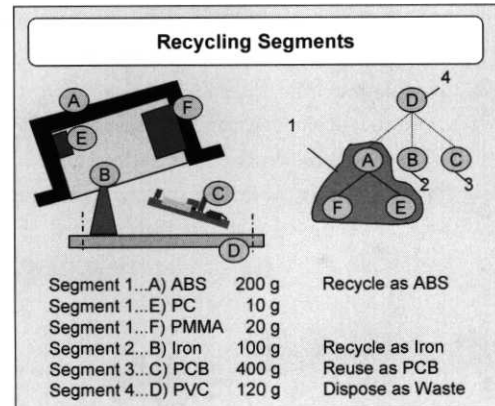


Figure 1. Recycling segments.

of an assembly process. So, the product does not always have to be fully dismantled. A group of parts can be recycled or disposed of with the same utilization without further dismantling.⁹⁾ This group of parts is called "segment" in this paper. A segment consists of one or more parts (see Figure 1).

The first step in building a segment is the determination of the starting point. The starting point is the first part to be selected for a segment creation. Estimation of starting values is required for determining a starting point. Each part of the product has its own starting value. The starting value basically means the profit or cost that can be generated by recycling or disposing of a part.

After starting values of all the parts have been calculated, suitable starting points are determined which meet the following requirements:

- Should be disassembled without disassembling any other parts
- Should not belong to any segments created previously
- Should not be reusable parts (a reusable part has its own segment)

The part which has the highest starting value of the suitable starting points is selected as the first starting point for the first segment creation. Assessment is then implemented on which parts connected directly or indirectly to the starting point belong to the first segment. This assessment is based on the optimization of the product's end-of-life cost. To estimate its end-of-life cost, the database for the disposal cost of waste or hazardous substances, the disassembly cost which depends on disassembly time and the recycling profit from valuable materials are needed. The end-of-life cost can be represented as:

$$C_{EoL} = P_{\text{recycling}} \text{ (or } C_{\text{disposal}}) + C_{\text{disassembly}} \quad (1)$$

where

C_{EoL} is the end-of-life cost, $P_{\text{recycling}}$ the recycling profit, C_{disposal} the disposal cost, $C_{\text{disassembly}}$ the disassembly cost

Once the first segment has been determined through the assessment, the next starting point is found as the same way done at the process of the first starting point determination. The next segment is then determined with the next starting point in the same way excluding the parts taken already for the former segments.

A segment may consist of:

- a reusable part
- a hazardous part or hazardous parts which include the same hazardous materials
- parts which can be recycled together, or
- parts which can not be recycled together

In general the product that consists of small number of recycling segments costs less for its end-of-life treatments than that which consists of relatively large number of recycling segments. The number of segments in a product means the optimal degree of disassembly for the lowest end-of-life cost. The optimal degree of disassembly can be found considering reuse and recycling profit, disposal costs and disassembly costs.

As shown in Figure 2 the added value, which is the net sum of reuse and recycling profit, disposal costs and disassembly costs, is found at

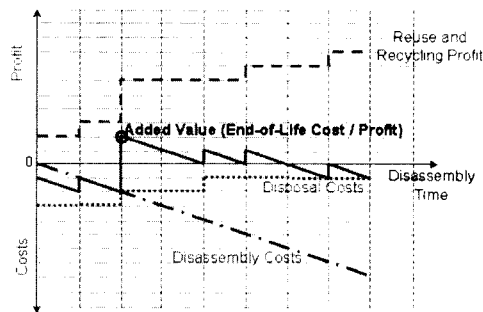


Figure 2. Recycling segment with a maximum added value.

a certain disassembly depth. Each segment is created when its maximum added value is obtained. It is not necessary to disassemble further beyond this point because the added value is getting decrease.

The eco-recycling rate of the product is determined based on the determined segments and their end-of-life destinations (recycling, reuse, disposal as waste or hazardous waste). The eco-recycling rate is introduced to reflect the economic efficiency of the product's end-of life using the concept of the recycling segment. Consequently, the eco-recycling rate written in the formula (2) considers all the factors influencing the design for recycling such as material features including its weight and type, joining techniques and product structure compared to the conventional recycling rate written in the formula (3) based on just materials.

$$\text{Eco-recycling rate} = f(\text{material features, product structure, joining techniques}) \quad (2)$$

$$\text{Conventional recycling rate} = f(\text{material features}) \quad (3)$$

Recycling Potential

The eco-recycling rate is the quantitative result based on the segment concept. It is useful for identifying the recycling performance of a product. It can thus be used for estimating the degree of improvement of a newly developing product. However, the eco-recycling rate is just an indicator representing the recycling perform-

Material	Structure	Joining techniques
1. Total Compatibility of Plastics	11. Total Parts Arrangement	18. Mechanical Connections
2. Part Compatibility of Plastics	12. Priority of Recyclable Parts	19. Cable Connections
3. Use of Recycled Plastics	13. Priority of Hazardous Waste Parts	20. Integration of Cables
4. Marking of Plastics	14. Accessibility	21. Variety of Joining Techniques
5. Marking of Hazardous Materials	15. Easy of handling	22. Joining Categories (per connection)
6. Variety of Plastics	16. Disassembly Direction of Parts	23. Variety of Screwing Tools
7. Preferred Materials	17. Disassembly Direction of Screw Joints	24. Variety of necessary Tools
8. Material Purity of Parts		25. Non-destructive Connections
9. Ratio of Disposal		26. Non-destructive Reusability
10. Ratio of Hazardous Disposal		27. Preferred Joining Techniques\
		28. Quantity of Joining Elements

Figure 3. Three Categories and 28 Criteria for the Recycling Potential.

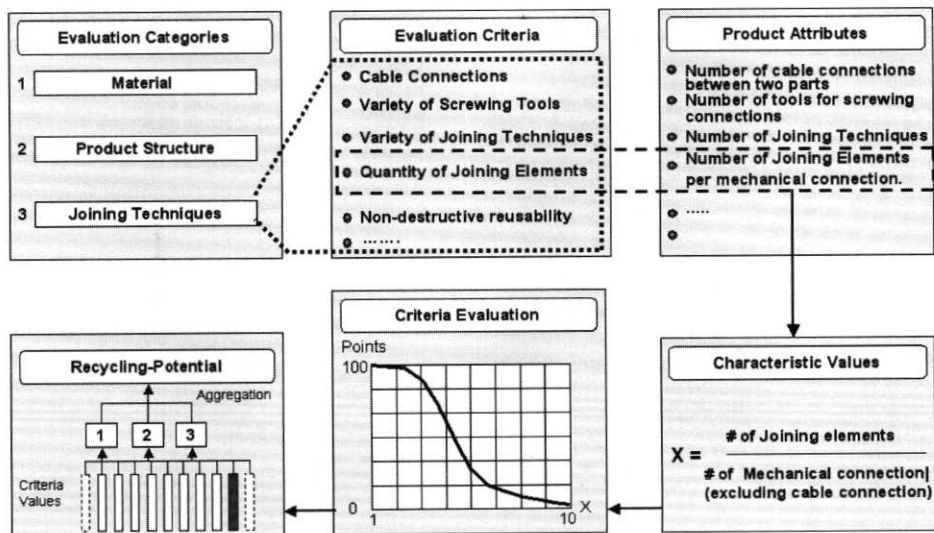


Figure 4. Assessment Flow for Calculating the Recycling Potential.

ance of a product. It suggests no recommendation for improvement. Thus an indicator which is able to identify the bottleneck points and their reasons may be required.⁷⁾

The eco-recycling rate is a function of materials' features, product structure and joining techniques as seen in the formula (2). To find the environmental bottlenecks and their improvement opportunities, three elements of the func-

tion should be investigated in detail. The recycling potential proposed in this research gives a detailed end-of-life information on these three elements. It helps a designer to recognize what the problems and clues exist for environmental improvements.

The recycling potential consists of 28 criteria which are classified into 3 categories (see Figure 3). These 28 criteria are all linked with product

attributes, respectively. Each criterion is evaluated based on its evaluation function regarding characteristic values which are associated with product attributes. Consequently, the recycling potential shows quantitative assessment results for each criterion and also gives an averaged value of 28 criteria evaluation results (see Figure 4).

For all criteria, a reference evaluation function is given as Eq. (4).

$$U(x) = \frac{100}{1 + 99 \cdot \left[\frac{X - X_{\max}}{X_{\min} - X_{\max}} \right]^p} \quad (4)$$

where $U(x)$ is the recycling potential, X_{\max} the characteristic value in best case, X_{\min} the characteristic value in worst case and p the distribution parameter.

For each criterion, a specific evaluation function is determined by defining X_{\min} , X_{\max} and p . Both extreme characteristic values vary with the characteristic of each criterion. The range of characteristic values in each criterion should reflect the actual situation of electronic appliances. While X_{\max} and X_{\min} define the range of the X-axis of the function, the distribution parameter p defines the distinctive curvature of the function for each criterion. Displacement of $U(x)$ for a unit range is getting bigger as X is getting closer to X_{\max} . The distribution parameter p is empirically determined based on the characteristic of each criterion (see Figure 5).

For instance, when $X=X_{\max}$, the recycling

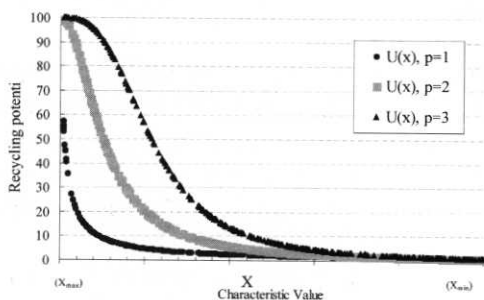


Figure 5. Variations of the evaluation function depending on the distribution parameter p .

potential $U(x)$ will be 100. On the other hand, $U(x)$ will be 1 when $X=X_{\min}$.

The specific evaluation function for each criterion is then generated with these three values, X_{\max} , X_{\min} and p , determined. A total of 28 evaluation functions are created for calculating the recycling potential. The recycling potential is expressed as an averaged value of these 28 evaluation results. It represents the level of the product's recycling-oriented design, and gives information on its environment-related weak points.

EoL-Performance

One of the EoL-EPES' elements, EoL-performance, has the function which supports the strategy establishment for improvement of a product's environmental aspects.

The geometric average of the two indicators, i.e., the eco recycling rate and the recycling potential, is called "EoL-Performance" which can be used for identifying the relative position of a product regarding its end-of-life environmental performance and for setting up the improvement strategy. The EoL-performance ranges from 0 to 100. For further analysis the EoL-performance is displayed in a portfolio chart where the recycling potential and the eco-recycling rate are X -axis and Y -axis, respectively. Based on the values of these two factors a product can be placed in one of the four areas of the chart (see Figure 6).

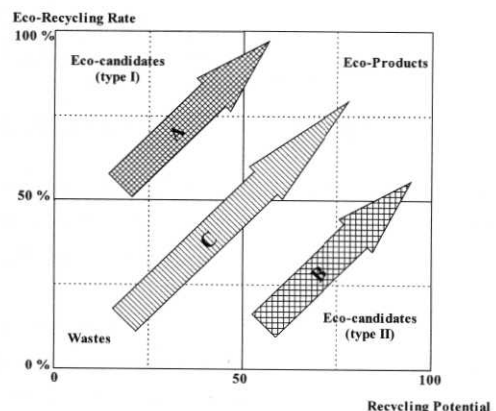


Figure 6. EoL-Performance Portfolio for strategic decision-making.

The EoL-Performance Portfolio is a matrix consisting of four partitions as follows:

The Eco-candidate, type I, exist in the upper left quadrant. They are products that have a relatively high eco-recycling rate despite of a low recycling potential, which are generally metals-dominated products. The reason for their higher recycling rate comes from the higher price of the metals than one of recycled plastics in the secondary market. This group of products may get into Eco-Products with relatively a little efforts. In order to achieve the strategy A in Figure 6, an improvement idea which is focused on structural redesign may be appropriate.

The Eco-candidate, type II, exist in the lower right quadrant. They are products that have a relatively low eco-recycling rate, but a high recycling potential. They are usually plastics-dominated products. Their low eco-recycling rate reflects the current situation, in which plastics' recycling is not economically beneficial. However, as intensified environmental legislations promote the development and application of new recycling technologies and subsequently accelerate the activation of secondary material markets, the eco-recycling rate of the product will probably be significantly increased. The strategy B may be obtained when the action for

improvement is focused on material substitution.

Wastes positioned at the lower left quadrant are products with a low recycling potential and a low eco-recycling rate. The achievement of the strategy C may be made from extensive redesign.

Eco-Products positioned at the upper right quadrant are products that have a high recycling potential as well as a high eco-recycling rate. This class of products may be better for business which can reduce the end-of-life cost and environmental impacts. A company can also declare the environmental benefits of the product to the public if the results are transparent and reliable.

APPLICATIONS

A number of products in various product types such as refrigerator, vacuum cleaner, washing machine, air conditioner and microwave oven were evaluated based on the EoL-EPES. The EoL-EPES application to products has been made to show the effectiveness of the EoL-EPES for ecodesign. The components' names of the product were written in an alphabetical form rather than their actual names due to the company secrecy. The components and the joining techniques used were streamlined for easy under-

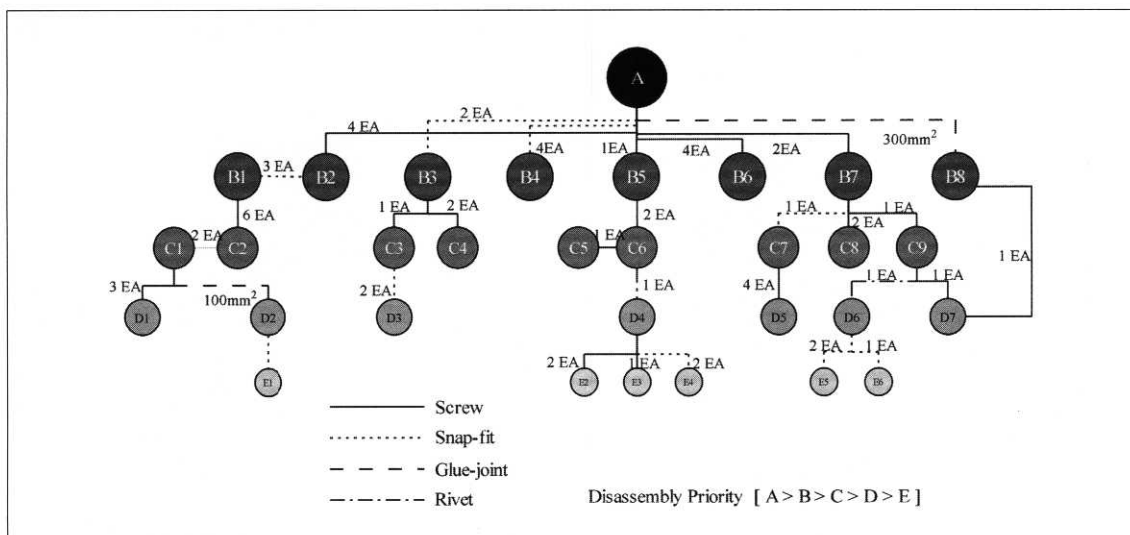


Figure 7. Components tree of the product.

standing.

Figure 7 shows the components tree of the product. The hierarchy of the components indicates the priority of disassembly. It means that the component A must be disassembled prior to disassembling the components B(1~8). Different connection lines represent the types of joining techniques.

The prerequisite information on the EoL-EPES, which is not shown in Figure 7, is briefly listed in Table 2.

Figure 8 shows portions of the product's material types. Assuming that the recyclable materials for the product with current technologies are steel, aluminum, copper, ABS, PP,

PS and non-hazardous PCB based on materials listed in Table 2, the conventional weight-based

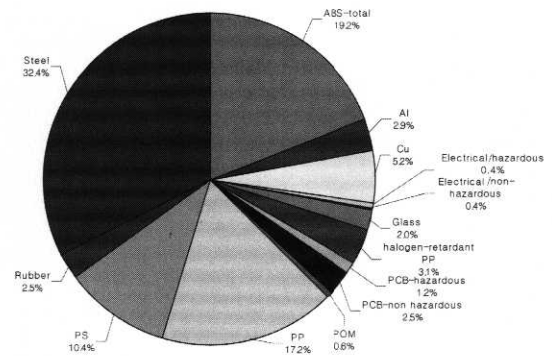


Figure 8. Portions of material types of the product.

Table 2. Parts information of the product

Parts information							
name	shape	max.size	accessibility	material type	weight	marking	hazardous
A	type1	400 mm	good	ABS	1,000 g	yes	no
B1	type2	400 mm	sufficient	PP	350 g	yes	no
B2	type1	350 mm	sufficient	PS	530 g	yes	no
B3	type5	200 mm	good	ABS	700 g	yes	no
B4	type4	300 mm	sufficient	PP	250 g	yes	no
B5	type2	400 mm	sufficient	Steel	2,000 g	yes	no
B6	type5	100 mm	good	PS	200 g	yes	no
B7	type5	120 mm	sufficient	PS	100 g	yes	no
B8	type2	150 mm	restricted	Rubber	200 g	no	no
C1	type1	150 mm	sufficient	halogen-retardant PP	150 g	yes	yes
C2	type5	400 mm	sufficient	PP	750 g	yes	no
C3	type2	180 mm	sufficient	halogen-retardant PP	100 g	yes	yes
C4	type4	200 mm	sufficient	PS	100 g	yes	no
C5	type6	30 mm	restricted	POM	20 g	no	no
C6	type2	120 mm	sufficient	PP	200 g	yes	no
C7	type4	110 mm	sufficient	PS	90 g	yes	no
C8	type5	230 mm	good	PS	40 g	no	no
C9	type2	200 mm	sufficient	PP	200 g	yes	no
D1	type3	130 mm	sufficient	PCB-non hazardous	250 g	no	no
D2	type4	40 mm	restricted	POM	20 g	no	no
D3	type2	100 mm	sufficient	PCB-hazardous	120 g	no	yes
D4	type4	300 mm	sufficient	Steel	1,300 g	-	no
D5	type6	20 mm	restricted	POM	25 g	no	no
D6	type2	100 mm	restricted	halogen-retardant PP	70 g	yes	yes
D7	type4	90 mm	restricted	ABS	250 g	yes	no
E1	type3	50 mm	restricted	Rubber	50 g	no	no
E2	type1	350 mm	sufficient	Cu	530 g	-	no
E3	type6	230 mm	restricted	Al	300 g	-	no
E4	type4	200 mm	sufficient	Glass	200 g	-	no
E5	type5	110 mm	sufficient	Electrical /non-hazardous	45 g	-	no
E6	type2	45 mm	sufficient	Electrical /hazardous	40 g	-	yes

recycling rate of the product results in 90%.

However, its eco-recycling rate is calculated as 57%. Some of the components which consist of recyclable materials may not be recycled due to economical reasons. In this case their structures or joining techniques make their end-of-life cost higher than their recycling profits. Their end-of-life destinations based on the eco-recycling rate are shown in Figure 9. A group of components represents a recycling segment which can be disassembled together.

The eco-recycling rate represents the economically optimal recycling rate which considers end-of-life costs and recycling profit. In order to improve the eco-recycling rate, environmentally weak points can be identified by the evaluation of the product's recycling potential.

The recycling potential of the product is 71 points which is obtained from the evaluation method described in the previous chapter. The points for 28 sub-criteria are shown in the Figure 10. The weak points in the criteria are "preferred joining techniques", "disassembly direction of screw joints", "accessibility", "total

part arrangement", "preferred materials", "marking of hazardous material", "use of recycled plastics" and "total compatibility of plastics".

Three criterias, i.e., "preferred joining techniques", "accessibility" and "marking of hazardous material" among 8 problematic criteria shown in Figure 10 were determined as the opportunities for improvement due to technical and economical feasibility in this study.

Several suggestions for environmental improvements have been applied to the product's redesign event. For example, the glued-joints between component A and B8 and between C1 and D2 are changed with 4 snap-fits and 2 snap-fits, respectively. The rivet connections are also changed into screw connections. Several components whose accessibility is restricted are changed into "sufficient". Marking of all the hazardous components has been made.

The conventional recycling ratio remains unchanged since the improvement has been implemented without material change. However the eco-recycling rate and the recycling potential have been improved from 57% to 68% and from

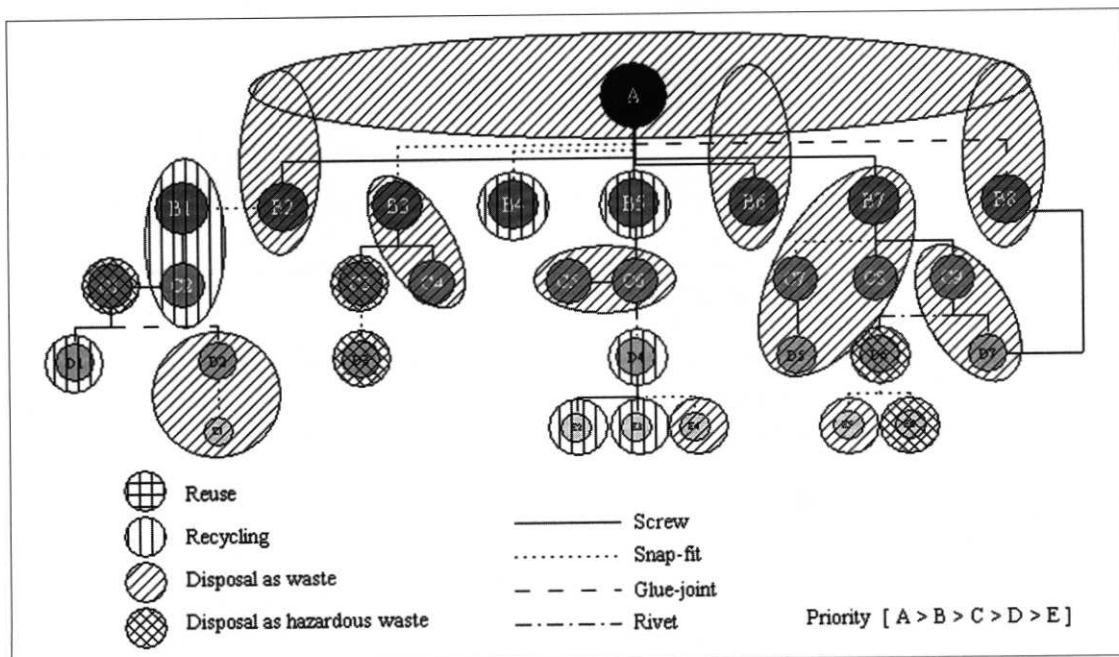


Figure 9. End-of-life destination of the components based on the eco-recycling rate.

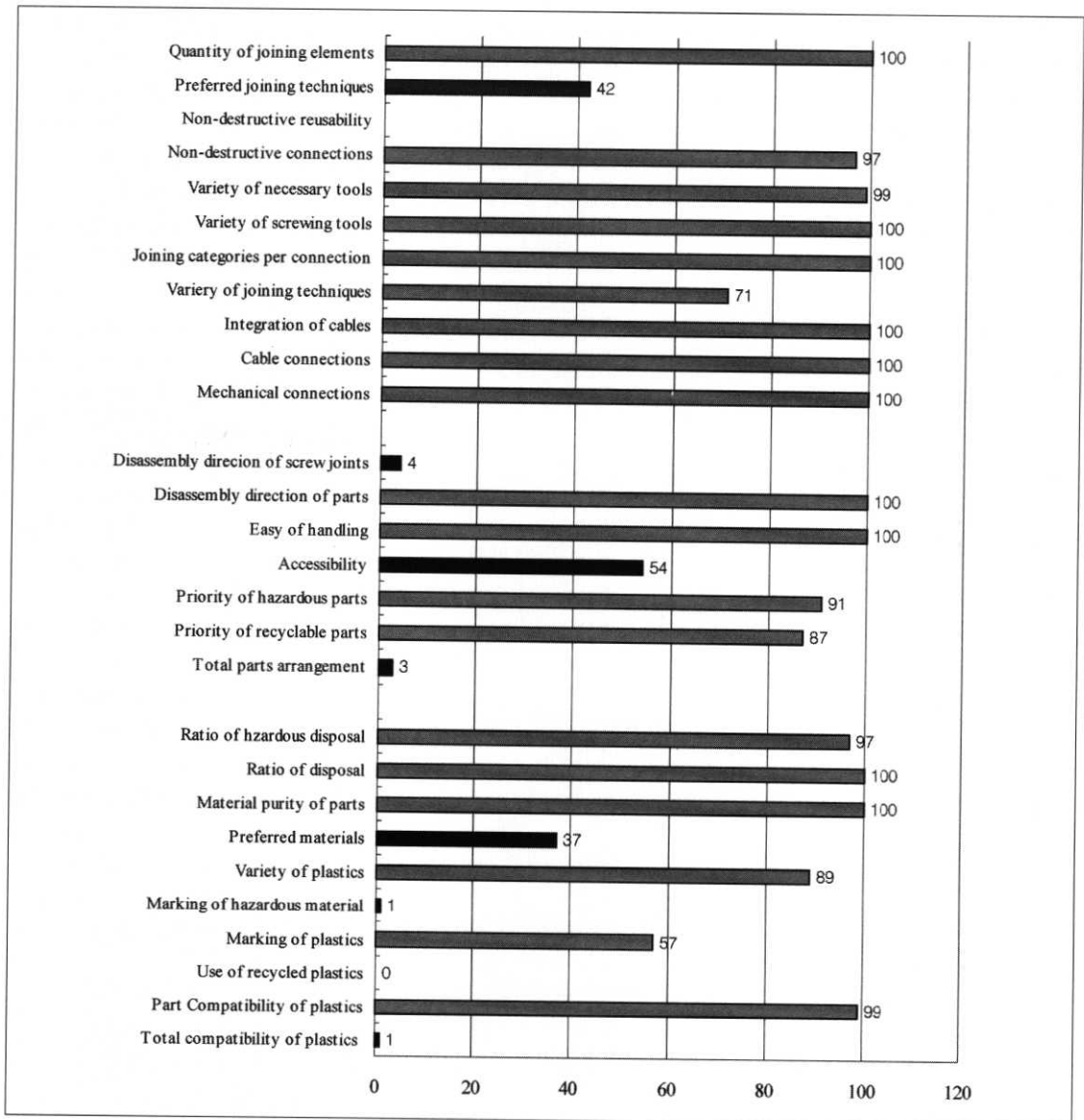


Figure 10. The recycling potential of the product.

71 points to 78 points, respectively. Consequently, the EoL-performance has been increased from 63.44 points to 72.92 points.

CONCLUSIONS

The EoL-EPES has been developed to support ecodesign activities in a company. It enables the systematic assessment of environmental performance of a product's end-of-life. The system which

consists of the eco-recycling rate, the recycling potential and the EoL-performance helps designers to integrate environmental aspects into their proposed design.

These three components may be systematically used in the ecodesign process of a company. The eco-recycling rate can be used as a suitable indicator in order that designers may identify the degree of recycling-oriented design of a product. Environmental performance of products whose

eco-recycling rate is lower than a certain limit can be evaluated and improved by the recycling potential. The recycling potential supports designers to recognize the clues for environmental improvement. The EoL-performance may be useful for setting up a company's strategic plan for a product's end-of-life improvement on environmental aspects.

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NOMENCLATURE

C_{EoL}	: End-of-Life Cost
$C_{disposal}$: Disposal Cost
$C_{disassembly}$: Disassembly Cost
EoL	: End of Life
EPES	: Environmental Performance Evaluation System
EPR	: Extended Producer Responsibility
PCB	: Printed Circuit Board
$P_{Recycling}$: Recycling Profit
WEEE	: Waste from Electrical and Electronic Equipment

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