Waste Management of Electric and Electronic Equipment: Comparative Analysis of End-of-life Strategies

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Abstract This article analyzes diverse aspects of the waste management of electronic and electric equipment. The scope of the study focuses on end-of-life strategies currently implemented in industrialized economies such as Japan, the United States, and the European Union. The objective is a comparative analysis of such strategies in order to identify logistic issues that may contribute to the further improvement of waste management policies. The results indicate that although all strategies follow the extended producer responsibility principle, in practice several logistic differences arise due to particular interpretations of the concept. In general, it was observed that a direct comparison is rather difficult since the strategies consider different legal frameworks, they cover different types and numbers of products, and the resultant mass flows and related operational costs are highly context-dependent variables. Therefore, it is not possible to indicate which strategy presents the highest overall efficiency. The study concludes that a little contribution is feasible if the advantages and weaknesses of the models depicted and discussed here are considered in further regulatory decisions.

Key words End-of-life strategy · WEEE · Waste management · Environmental management · EOL

Introduction

During the last few decades, the electronic and electric industries have presented accelerated growth aided by sustained technological development.¹,² Such a trend leads to the rapid replacement and disposal of products even before the end of their functional cycles.² The rising flow of discarded products is usually included in the municipal solid waste stream. Therefore, the common end-of-life (EOL) route for these waste products is disposal into landfill or incineration.¹ It is known that this practice leads to severe environmental impacts and significant losses of valuable components, materials, and energy.¹ Hence, new regulatory frameworks have been implemented in order to prevent such negative effects. With a focus on the extended producer responsibility (EPR) principle,³ most contemporary regulations attempt the diversification of EOL strategies from common disposal. In this context, recycling and re-use are emerging as formal downstream activities with potential benefits for the environment and the economy.³,⁴ This article analyzes and discusses the performance and logistic aspects of EOL strategies for electronic and electric equipment currently implemented in Japan, the United States, and the European Union. A comparative analysis of such strategies is also given and discussed in order to identify logistic issues that may contribute to the further improvement of waste management policies. The next section introduces the relevant concepts and aspects according to the scope of this study.

Theory

All products have a life cycle that covers a sequence of interrelated stages from the acquisition of raw materials until their end-of-life, when the product’s functionality no longer satisfies the requirements of the original owner.² At the end of life, the product can be disposed of or its life cycle extended over time²,⁴ (Fig. 1). There are five basic end-of-life strategies. In accordance with their potential economic and
environmental efficiency, the strategies can be ranked as follows:\textsuperscript{2,5}

1. re-use;
2. servicing;
3. remanufacturing;
4. recycling;
5. disposal.

\textit{Re-use} represents the recovery and trade of used products or their components as originally designed. \textit{Servicing} is a strategy aimed at extending the usage stage of a product by repair or maintenance. \textit{Remanufacturing} considers the process of removing specific parts of the waste product for further re-use in new artifacts. \textit{Recycling} (with or without disassembly) includes the treatment, recovery, and reprocessing of materials contained in used products or components in order to replace virgin materials in the production of new goods. Finally, \textit{disposal} entails the processes incineration (with or without energy recovery) or landfill. Frequently, EOL strategies are combined in order to maximize profitability and efficiency.\textsuperscript{2,4,5}

In general terms, it is known that both the \textit{design process} and the \textit{collection method} to recover discarded products have a fundamental role in determining the efficiency of a given end-of-life strategy.\textsuperscript{3} The design process defines all product characteristics such as material composition, performance, and costs.\textsuperscript{4} Therefore, design has an implicit role in defining the best end-of-life practice for a given product.\textsuperscript{2,4,5} In this context, the \textit{design toolbox} or “design for X” (DFx) in a contemporary design process is an integrative method for cost-effective and high-quality life-cycle management.\textsuperscript{3} Some examples of DFx in relation to specific EOL issues are the design for environment (DfE or eco-design), disassembly, serviceability, re-use, repair, and recycling.\textsuperscript{4}

On the other hand, the \textit{collection method} entails the action of recovering waste products once they are discarded.\textsuperscript{6} In general, the volume and quality of the incoming flow of recovered products constrains the efficiency of certain EOL strategies such as recycling and re-use.\textsuperscript{5,6} The most common collection methods are based on five models:\textsuperscript{5}

1. drop-off;
2. permanent collection depot;
3. curbside collection;
4. point-of-purchase;
5. combined/coordinated.

The \textit{drop-off model} is a 1-day collection event that is generally organized using existing municipal facilities. The \textit{permanent collection depot} is a continuous event in which a designated site is permanently used for the collection and temporary storage of specific types of products. The \textit{curbside collection}, in contrast, means the recovery of used products or wastes either on a periodic basis or by request. The \textit{point-of-purchase model} is the collection of used products by a retailer. Finally, a \textit{combined/coordinated model} is a program in which various collection methods are implemented simultaneously. Another concept closely related to EOL strategies is product \textit{take-back}, aimed at recovering sold products or their components for specific industrial purposes such as recycling or re-use.\textsuperscript{6} Often, a take-back system is based on either a point-of-purchase model or curbside collection by request.\textsuperscript{5}

When choosing an EOL strategy for a given product, diverse logistic and environmental issues need to be considered. In particular, electric and electronic equipment has a high residual value after discard.\textsuperscript{1} In fact, a significant amount of disposed equipment is appropriate for re-use or remanufacturing. In addition, the material composition of these products allows profitable recycling.\textsuperscript{6} Table 1 shows the average material composition of four Japanese electric appliances.\textsuperscript{1,7,8} From an environmental point of view, the most significant impacts throughout the product’s life cycle occur during the usage stage, followed by the extraction of raw materials and disposal.\textsuperscript{1,2} This particular situation implies that EOL strategies must focus on reducing the impacts at three different life-cycle stages. Therefore, it is likely that an adequate EOL scenario for these products requires the integration of several strategies into a coordinated logistic system. Such a system entails the adjustment of the design process to diverse demands, the adequate implementation of a take-back program, an appropriate infrastructure, and the development of an efficient business model. All these factors represent the coordinated participation of the corporate and social participants in the system. In this context, the \textit{extended producer responsibility} (EPR) principle\textsuperscript{7} has been one of the main driving forces while regulatory frameworks for the environmental and economic management of waste electronic and electric products have been developed. EPR is the principle in which\textsuperscript{7}

\begin{itemize}
  \item Actors along the product chain share responsibility for the lifecycle environmental impacts of the whole product system. The greater the ability of the actor to influence the
\end{itemize}
These actors are the consumers, the suppliers, and the product manufacturers. Consumers can affect the environmental impacts of products in a number of ways: via purchase choices (choosing environmentally friendly products), via maintenance and the environmentally conscious operation of products, and via careful disposal (e.g., separated disposal of appliances for recycling). Suppliers may have a significant influence by providing manufacturers with environmentally friendly materials and components. Manufacturers can reduce the life-cycle environmental impacts of their products through their influence on product design, material choices, manufacturing processes, product delivery, and product system support.

From an economic perspective, EPR is a referential strategy to promote the integration of the environmental costs associated with product life cycles into the market prices of the products. This economic approach to EPR focuses on the role of producers, and consequently of corporate organizations. The minimization and prevention of wastes, the increased use of recycled materials in production, and the internalization of environmental costs in product prices are fundamental while implementing an EPR program in companies. In this context, the responsibility of the producers lies in a legal duty enforced by governments or in a voluntary action. Whatever the nature of an EPR program (voluntary or mandatory), from the point of view of a company which is still responsible for its own products, the objectives imply the creation of a system that conserves materials over the entire product life cycle and the implementation of systems and facilities for product recovery. Therefore, the responsibility for product recovery has become essentially synonymous with product take-back. The potential environmental benefits of EPR include the efficient use of resources, cleaner products and technologies, an efficient reduction in manufacturing and the banning of hazardous substances used in production, increased recycling and recovery, and greener consumption. All these benefits are gained while internalizing environmental issues (and costs) in the product chain.

### Analysis

This section includes an analysis of different EOL strategies for electronic and electric equipment currently implemented in Japan, the United States, and the European Union. The focus of the analysis is on either qualitative or quantitative aspects.

#### Japan

In April 2001, under the current legislation on waste disposal and the promotion of efficient utilization of resources, the Japanese government enforced the Designated House-
Appliance Recycling Law (DHARL). This basic policy, based on an interpretation of the EPR principle, concerns the collection, transportation, and recycling of waste products from household appliances such as TV sets, air-conditioner units, refrigerators, and washing machines. Together, the four targeted products represent 80% of the total number of appliances discarded by householders, and approximately 2% of the total municipal solid waste generated annually in Japan. This percentage represents about 20 million units discarded annually, and an equivalent mass of 733,000 tons.

DHARL represents the first attempt to implement a full-scale private-sector-based post-consumer waste recycling system in Japan. The system entails the coordinated participation of several stakeholders such as manufacturers and importers, retailers, consumers, and municipal offices (Fig. 2). Manufacturers and importers have an obligation to take back their products at designated collection sites, and to recycle them according to standards set by the government. In this context, recycling is defined as the action of removing valuable parts and materials and re-using them as substitutes in manufacturing or as fuel (thermal recycling). The current recycling target for air-conditioners is 60%, 55% for TVs, and 50% for refrigerators and washing machines. Alternatively, retailers are requested to take back used home appliances that they have sold and to transfer them to the corresponding manufacturer or importer. Municipal offices can also collect discarded appliances in order to transfer them to manufacturers or “independent bodies” for recycling. However, in some cases municipalities are allowed to perform recycling activities. Consumers are obliged to cooperate in transferring used appliances to retailers or municipalities, and to pay the necessary fees for collection, transportation, and recycling. Such fees range from 2400 to 4600 yen for recycling, and from 2500 to 5000 yen for collection. Therefore, the Japanese strategy is an obligatory take-back system broadly based on combined kerbside and point-of-purchase collection programs.

At the national level there are two recycling business groups, A and B, currently operating under the DHARL. The A group comprises 14 industrial corporations, including the Matsushita Electric Industry, Toshiba, the Japanese Victor Company, and the Daikin Industry. The group assigns 190 designated points for collection and 24 recycling plants. The B group comprises 20 corporations, including Mitsubishi Electric, Sharp, and Sanyo Electric. This group also provides 190 collection points but only 14 recycling plants. The two groups provide the necessary technological and economic structure for the collection, recycling, and reutilization of 600,000 tons/year of discarded appliances. The groups have adopted a standard recycling system, which includes a series of stages. After collection, products are delivered to the recycling plant to be sorted, treated, dismantled, and crushed. Valuable materials such as glass, aluminum, certain types of plastics, copper, and iron are recovered with a high level of purity via electromagnetic, centrifugal, and gravity separation techniques. Hazardous substances are recovered and destroyed via thermal or chemical processes. After recycling, materials are re-used in manufacturing new products (see Fig. 2). In general terms, this end-of-life strategy focuses on recycling with or without disassembly. Therefore, in companies the design toolbox has been broadly focused on design for disassembly and recycling.

United States of America

Motivated by the adoption of the EPR principle, the United States developed several initiatives regarding the recycling and re-use of end-of-life electronic products. Sponsored by the Environmental Protection Agency (EPA), the National Electronics Product Stewardship Initiative (NEPSI), proposed in 1999, was aimed at financing a national recycling system with a focus on TVs and personal computers. At federal level, also under the coordination of the EPA,
several programs and pilots have been implemented. Two examples are the WasteWise plan on the recycling and re-use computer hardware, and the Computer Display Project with a focus on recycling the cathode ray tubes (CRTs) contained in TV sets and computer monitors. In a more advanced stage of development, the Electronic Product Recovery and Recycling Project (EPR2) is aimed at encouraging the recycling and re-use of diverse electronic equipment via the implementation of cost-effective demanufacturing processes.

Case 1, the EPR2 pilot

The EPR2 initiative considers a series of pilot programs in different geographic locations, diverse collection methods, and different data sets. The program covers five collection bases located in Binghamton/Somerville, Naperville/Wheaton, Union County, Hennepin County, and San Jose. The pilots focused on the collection of over ten domestic products classified into five categories. Among the targeted products, TVs, computers, printers, VCRs, audio equipment, and telephones showed the highest collection rates. In all cases, the participation of concerned stakeholders was voluntary, and local authorities and businesses shared collection and recycling costs. Therefore, no operational costs were charged to consumers. Figure 3 shows the general end-of-life strategy implemented in the pilot. The strategy focuses on the reduction of incoming flows of wastes to landfills or incinerators while maintaining profitability. Priority is given to the extended lifespan of products or components via repair and re-use. When re-use is not possible, products are disassembled and the components are refurbished for re-use in domestic or overseas industries. Recycling takes place when no other re-use route is feasible. This strategy attempts the maximal reduction of hazardous waste inputs into landfill sites or incinerators. From an economic viewpoint, the study concluded that the net costs of the pilot were broadly driven by demanufacturing costs. Moreover, the kerbside collection method presented the highest efficiency.

Case 2, the Massachusetts initiative on demanufacturing

The Massachusetts initiative covered only two products for collection, i.e., TV sets and computer equipment. The pilot covered 48 recycling plants, 196 repair shops, 4 collection agencies, 10 charity/re-use facilities, 2 retailers, and 32 exporters of electronic equipment. Although the main goal of this initiative was the recovery and recycling of the CRTs contained in screens and monitors, the general approach coincides with the end-of-life strategy depicted in Fig. 3. It was estimated that the frequency of collection and the physical condition of the equipment recovered are important constraints for the efficiency of the strategy. In addition, it was found that re-use and repair, for either domestic consumption or export, are the most cost-effective end-of-life routes. In this context, the material recovered for re-use or repair can be more than ten times as valuable as the recycled material (scrap).

In general, both pilots indicated that the participation of the stakeholders was satisfactory, but the results were less profitable than expected. The overall recycling costs were about 44560 yen/ton, and the collection costs varied between 28441 and 48022 yen/ton. In this context, it was found that additional collection fees to consumers are required in order to increase the overall profitability of the current business model. Although neither of the pilots covered specific aspects regarding the design toolbox, it has been reported that the EPA is currently coordinating a national initiative on DfE with the electronics industry in order to improve the efficiency of demanufacturing. Considering that both initiatives emphasized re-use and repair,
it is likely that the toolbox initiative will broadly focus on
design for disassembly, repair, and re-use.

**European Union**

The current end-of-life model in the European Union (EU) is based on the *Directive on Waste from Electronics and Electronic Equipment (WEEE)*\(^\text{15}\) and the *Directive on Restriction of Hazardous Substances (RoHS)*\(^\text{16}\) approved in October 2002. The initiative covers 81 products divided into ten categories from small domestic appliances to medical equipment. The WEEE directive attempts to standardize the requirements for the collection and recycling of electronics in the community, but also to extend the regulations to imported products. The objective of the directive is to prevent waste generation by encouraging re-use, recycling, and other forms of recovery, and to improve the overall environmental performance of products during their life cycle. The scope of this directive includes producers, distributors, consumers, and all parties involved in treatment of the waste. Producers are requested to finance the collection, treatment, recovery, and environmentally sound disposal of used products or wastes from households and other entities. The RoHS directive bans the trade of any new equipment containing mercury, lead, cadmium, hexavalent chromium, polybrominated biphenyls, or polybrominated diphenyl ethers. This initiative is expected to have a great influence on the current design process and disposal methods.

As a complementary measure, the Community has recently dictated new legislation aimed at regulating design innovation in the electronics and electrical industries.\(^\text{17}\) Under this proposal, manufacturers selling their equipment in the European Community would have to perform a *conformity assessment* of their products according to specific DfE guidelines.\(^\text{17}\) The implementation of an “*internal design control*” to satisfy the basic product requirements becomes mandatory, and manufacturers who comply will be awarded an “EC label” of product certification conformity. Full implementation of the directive is expected at the end of 2006. In the context of end-of-life methods, the initiative encourages design for disassembly, re-use, repair, and recycling.

**Case 1, the WEEED\(^\text{15}\)**

The WEEE directive imposes a high recycling rate for all targeted products. The rate varies from 50% to over 80%. The recovery consists of a take-back system with combined collection methods. The projected annual yield is 4 kg/inhabitant. The end-of-life strategy focuses on collective re-use and recycling. The strategy includes the following sequence of processes: collection, sorting, refurbishment, dismantling, shredding, treatment of recyclable components/materials, treatment of hazardous components/substances, and landfill or incineration (with heat recovery) of remaining wastes. This strategy is based on “additive systems” consistent with ISO 14040. Figure 4 illustrates the WEEED strategy. Collection costs fluctuate between 27,000 and 54,000 yen/ton depending on the product’s characteristics. The recycling costs, which are expected to decrease over time, vary from 1350 to 67,500 yen/ton.

**Case 2, WEEED in the United Kingdom\(^\text{16}\)**

The current EOL strategy in the United Kingdom has been designed to conform to the WEEE directive (see Fig. 4). In a trial stage, the study covered only six of the products included in the directive, i.e., refrigerators, washing machines, personal computers, TV sets, vacuum cleaners, and lawnmowers. The primary achievements throughout the
implementation differ from the projected results in the directive. The treatment and disposal of all products is not cost-effective except for personal computers. Such a deficit is broadly driven by collection and refurbishment costs. However, the overall costs of the system are lower than in the WEEE directive.

Results

Table 2 summarizes the results of the comparative analysis of qualitative and quantitative variables gathered from the different end-of-life strategies within the scope of this study. In order to standardize the quantitative data, all monetary values have been converted to Japanese yen (exchange rate in September 2003: 1 US$ = 119 yen, 1 Euro = 134 yen), and material flows have been expressed in yen/ton. As can be seen from Table 2, the European strategy covers the highest number and categories of products for recovery. The collection system differs among strategies. The Japanese strategy is unique in that it currently implements a mandatory take-back. The American strategy shows the lowest waste stream because of the small scale of the pilots. In terms of EOL routes, the Japanese strategy shows the highest achievement in recycling and the lowest re-use rate. The American strategy presents the lowest disposal rate, and the European Union shows the highest repair rate. Regarding costs, the Japanese strategy presents the highest operational costs. Among the strategies, the Japanese is unique in charging operational costs to consumers. The recycling system does not differ significantly among strategies in terms of recycling method and the treatment of hazardous substances. However, the American strategy considers the export of materials or components, unlike the “in house” approach of Japan and Europe. Another difference arises when comparing recycling targets, since Japan and the European Community consider minimal rates only. In this respect, the European Community presents the highest recycling target.

Discussion

The Japanese strategy, which broadly focuses on recycling, presents certain advantages in terms of collection rates, recycling efficiency, and pollution abatement. However, operational costs are significantly higher than in the other two models due to elevated expenditure on capital investment, labor, services, taxes, and technological developments. Because consumers absorb such costs, the
economic model of this strategy is highly dependent on the consumer’s willingness to pay, and consequently is dependent on consumer behavior. In this context, producers are requested to reduce fees as much as possible in order to increase consumer participation. This is expected to occur while intensifying the competition between the two recycling business groups currently in operation. However, the strategy for costs reductions in the two groups differs enormously. The A group focuses on maximal use of the existing recycling infrastructure, and therefore its strategy to reduce costs broadly depends on business expansion into other products in order to increase profitability. The operational costs in the B group are driven by the initial investment in infrastructure and potential turnover. It has been shown that the current business model requires a radical expansion of its market in order to improve competitiveness. The potential annual market of the four products covered by the recycling law is restricted to 100 billion yen. This could rise to over 300 billions yen if additional products such as computers and mobile telephones are included in the law. Nevertheless, the current Japanese EOL strategy presents the highest associated social expenditure of all the models. This particular situation can be explained by an inadequate interpretation of the EPR principle in which the recycling law was conceived. Although consumers are seen as important actors in the EPR principle, their role is limited in terms of economic responsibility. This is due to the implicit role of corporate organizations while internalizing the environmental costs in product prices, as occurs in the European strategy.

In this context, the WEEE directive indicates that, in the long-term, the price of new products will not be significantly affected by the internalization of environmental costs, since the demand for most types of electronic product is inelastic. In the American approach, costs are likely to be shared by local authority recycling agencies, but it has been shown that in order to increase the overall profitability, additional fees may have to be paid by consumers. However, it was observed that the consumer’s willingness to pay is very low.

Since the business model of the Japanese strategy broadly depends on the recycling efficiency, factors diverting the incoming flow of waste products are considered to be important operational constraints. Among these, the export of used appliances (often overlooked) and unlawful dumping have been shown to be serious barriers to the model. It has been shown that the combined effect of these factors can potentially reduce the material input for recycling by 40%.

The Japanese recycling system is broadly technology-driven. Therefore, the efficiency of the system is directly influenced by state-of-the-art technology. Nowadays, the system presents certain advantages when recovering materials with high purity. This allows the use of such materials in diverse manufacturing processes while keeping an overall high profitability.

Although the current average recycling target in the Japanese strategy is lower than the European one (15%–25% less), the total mass recovered after recycling is slightly higher. This “hidden mass” is the result of a different definition of recycling. In Japan, only recovered materials with positive value for upstream activities are counted as recycled. For example, about 75% of the total recovered plastics from appliances in Japan do not have value for upstream domestic activities, and consequently only a potential 25% of the total recovered plastics can be considered as recycled. We assume that all the materials without a positive residual value are either disposed into landfills or incinerated. However, in the European model, all materials physically recovered in the process of recycling, whatever their residual value, are considered as recycled. On the other hand, the American model regards recycling as a subprocess of demanufacture. This subprocess consists of the reduction of assemble parts into material scrap after re-use or refurbishment has been shown to be impossible. Therefore, only the fraction of the product that is reduced to scrap is considered as recycled. Thus, the American strategy does not impose referential recycling targets to demanufacturers because the main premise behind the strategy is to reduce the material input into the disposal routes via re-use as much as possible. In this context, the pilot projects achieved disposal rates below 5%, i.e., the lowest among the strategies. However, it is important to mention that the American strategy considers a high export rate of products, components, and materials. Conversely, the Japanese and European models, are “in-house” systems in which all material flows are to be treated, re-used, and disposed of through domestic boundaries.

Another important conceptual difference among the models concerns the definition of re-use. In the American and European models, re-use means the action of re-using discarded products or their components as originally designed while keeping their original functionality intact. In the Japanese strategy, re-use means the re-use of recovered materials (and probably certain components) in the manufacture of new products.

Regarding collection efficiency, it was observed that combined methods present a better cost-effective performance due to the allowed logistical flexibility. It was also shown that the logistical distribution of collection points with respect to recycling agencies had a significant impact on the overall cost-effectiveness of the system since transportation costs have a considerable weight in the total net expenditure.

Regarding environmental aspects, it was found that the Japanese strategy is broadly oriented to end-of-life impacts associated with landfill and incineration. Although the American strategy has a similar purpose, its emphasis on reuse and repair may result in further environmental benefits throughout the product’s life cycle. On the other hand, the European strategy emphasizes the necessity of a life-cycle approach while focusing on the implicit role of the design process in this issue. In this context, the Japanese strategy has restricted the optimization of the design toolbox to disassembly and recycling, while the American strategy has been focused on re-use and disassembly.
Conclusions

We conducted a comparative analysis of several end-of-life strategies for electronic and electric equipment implemented in Japan, the United States, and the European Union. The EOL strategies analyzed show important conceptual and logistical differences that make it difficult to carry out such a comparison. Hence, the results of this study should be treated with caution. Nevertheless, it is possible to conclude that current EOL strategies regarding WEEE present economic and environmental advantages compared with traditional disposal practices. Although recycling was the predominant EOL route observed in this study, it has been shown that re-use presents greater benefits for both the environment and the economy. We therefore concluded that further improvements in waste management policies regarding WEEE should focus on re-use and related strategies, such as servicing, while giving a complementary status to recycling. This implies additional considerations regarding the diversification of the design toolbox during the product development process, as well as the creation of new business models for a service-oriented economy.

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