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An Analysis of Product Properties Affecting Performance of End-of-life Systems for Electrical and Electronics Equipment

Abstract

Purpose - On the basis of empirical studies this paper aims at identifying and analysing product properties that affect performance of end-of-life systems for electrical and electronic equipment (EEE).

Design/Methodology/Approach – The research was carried out as case studies of end-of-life management of EEE. Case A focused on disassembly of computer screens and TV-sets, whereas Case B addressed logistics systems for recycling of various types of EEE. Data collection methods include interviews, on-site visits and observations, video recording, and studies of documents.

Findings – Nine product properties that affect performance of end-of-life systems for EEE are identified. The properties relate to three different product levels: the product assortment level, the product structure level, and the component level. A model is presented which indicates that choices made and decisions taken in the product development process affect the end-of-life system performance. Application of modular product architectures and component standardisation are suggested as relevant design strategies during product development.

Practical implications - The implications for managers are that the findings presented in this paper provide strengthened arguments that modular product architectures and component standardisation are favourable approaches to apply in product development. Complementary to the benefits for manufacturing and logistics also end-of-life system performance will improve when these approaches are applied.

Originality/Value - Previous research has indicated some product properties that are supposed to influence performance of end-of-life systems. These properties originate primarily from conceptual discussions rather than empirical studies. This paper add to current understanding by presenting empirically based insights regarding which specific product properties affect performance.

Key words Electrical and electronic equipment (EEE), End-of-life systems, Product properties, Product development, Logistics

Paper type Case study

Introduction

Electrical and electronic equipment (EEE) manufacturers increasingly face environmental challenges. For example, the European Union (EU) has launched a number of directives targeted specifically towards EEE. The 'Restriction of Hazardous Substances Directive' (RoHS) require new materials and processes to be implemented in the design and manufacturing of EEE, whereas the 'Waste from Electrical and Electronic Equipment Directive' (WEEE) specifically addresses end-of-life management of EEE (European Parliament and the Council 2003 a,b). The recent directive on 'Ecodesign of energy-using products' (EuP) targets products that are dependent on energy input to work as intended, or products for generation, transfer and measurement of such energy (European Parliament and the Council 2005). Examples of such products include EEE and heating equipment.

According to the WEEE directive, EU member states should have end-of-life systems running from 1 July 2006. These systems include the collection, pre-treatment and recycling of EEE. The systems seem to be working and in 2005 the most advanced take-back systems operating in 11 countries collected 428,600 tonnes of end-of-life EEE (Leal, 2007). In Sweden, for example, the nationwide system Elretur is run by the company El-kretsen, which is owned by some 20 industrial organizations in cooperation with all the municipals of Sweden. The system includes two basic components: some 1,000 collection points provided by the municipals at which households can dispose end-of-life EEE free of charge, and transportation service of the collected EEE for pre-treatment and recycling in accordance with legal requirements. Member fees finance El-Kretsen and are calculated based on the volumes of new sales declared by the members. Since El-Kretsen handles a wide variety of products, specific solutions concerning fee structuring, product range and level of the collection service has been developed to fit each field of industry.

Basically, performance of the end-of-life systems are set by the properties of the devices handled within the system. An intricate feature of end-of-life systems is that these systems have to handle products of extremely low, or sometimes even negative, value (Anderson and Huge Brodin, 2005). Cost and efficiency of the end-of-life system is critical, i.e. performance related to collection, pre-treatment in terms of disassembly, refurbish of components, materials recycling, etc. As the product properties affect end-of-life systems performance it can be argued that the fee structuring, directly or indirectly, is associated with these properties. Products that possess properties that support efficient end-of-life systems should have possibilities to benefit from lower fees than products that do not possess such properties.

Previous research has indicated some product properties that are supposed to influence performance of the end-of-life systems (e.g. Jahre, 1995; McKinnon 1995; Chandrashekar and Dougless 1996; Knemeyer et al. 2002). Though a few of these properties have been identified in experimental research (e.g. Chiodo et al, 2001), many of the properties originate from conceptual discussions rather than empirical studies (e.g. Luttrupp, 1997; Sundin, 2001, Sundin, 2004). It can therefore be argued that there is a lack of understanding regarding which properties affect end-of-life system performance. Based on the rising societal demands on waste reduction there is a need for further knowledge of these product properties and how they influence the possibilities to achieve highly performing end-of-life systems. The present paper aims at reducing the flaw in current understanding. On the basis of empirical studies within the EEE industry a number of product properties are presented and analysed.

The remainder of the paper is structured as follows. First, previous research on product properties is presented. Then the research method is described. Thereafter the results are presented, including the empirical findings and an analysis of the findings. Strategies for developing products that support end-of-life system performance are then presented and the paper ends with some conclusions and a discussion.

Product properties

A vast number of requirements are set on a product including functionality, low price, nice appearance, reliability, etc. The various requirements must be considered when a product is designed and attained by providing the product its suitable properties. According to Hubka and Eder (1988), there are a few elementary design properties: product structure, form, material, dimension, surface quality, tolerances, and manufacturing method, that ultimately determine to which degree the requirements are fulfilled. These elementary design properties constitute the fundamentals of a model presenting different layers of product properties (see figure 1). The elementary design properties provide the product its internal properties, which consist of the relationship between the elements in a product and the properties of those elements. The internal properties constitute the foundation for the external properties that can be defined as the relationship of a product to its surroundings. An example of the links between the different layers of properties is that the product quality (product requirement) includes its reliability (external property), which is influenced by its manufacturing properties (internal property) that ultimately are defined by the product structure, materials choice, tolerances, etc. (elementary properties).

Product requirements	Law/Regulations, Longevity, Maintenance, Appearance, Price, Quality, Weight/Mass, Function, Recycling, etc.
External properties	Reliability, Manufacturability, Ergonomic properties, Operational properties, Aesthetic properties, etc.
Internal properties	Strength, Manufacturing properties, Corrosion resistance, Durability, etc.
Elementary design properties	Structure, Form, Material, Dimension, Surface quality, Tolerances, and Manufacturing methods

Figure 1: Relationships between various types of product properties (Based on Hubka and Eder, 1988).

In the literature, product properties have been addressed from different perspectives, including product properties associated with design of components and complex products (Ringstad, 1996; Liedholm, 1999), reverse engineering (Zhongwei, 2004; Corbo et al, 2004), and design for manufacturing (Wagne, 1995; Herbertsson, 1999; Eskilander, 2001). For example, the efficiency of manufacturing systems depends on the fit between the product and the manufacturing system (Adler, 1995) and a number of product properties are crucial for the manufacturing performance including bending/torsion stiffness, ease of maintenance, ease of fault diagnostic, component durability, component finish, etc. Rampersad (1994) presents

three types of properties essential for the link between the product design and the manufacturing system efficiency, i.e. assembly properties (e.g. weight, length), component properties (e.g. stiffness, symmetry), and process properties (e.g. composing direction, alignment). The two first types of properties are directly related to the product design, whereas the latter is primarily related to the manufacturing system *per se*. Other studies have revealed a few properties (e.g. product complexity and variety), which affect manufacturing ramp-up performance (e.g. Berg, 2007). These properties are directly or indirectly related to the product design. It has also been claimed that the interrelationships between the product design and the manufacturing system relates to different product levels, including the corporate level, product family level, product structure level, component level (Fabricius, 1994). The corporate level addresses the interaction between the product and other types of products in the company. The family level refers to the relationships between different variants within the same product family. The product structure level concerns the relationships between the various sub-systems/components. The component level refers to the design/specification of each individual component. The various product properties must be considered at each of these product levels.

Another area, which to some extent has attracted interest for product properties, is logistics. However, most authors simply address the products and their properties' influence on the logistics system performance implicitly. A range of product properties that affects the performance can be identified and structured into; handling properties, complexity, variety, and value. The handling properties influence how the product can or must be handled within a distribution or a supply system. Research into this area is scarce, and knowledge on handling properties coupled with total system performance is mainly found in textbooks. The handling property is, in turn, influenced by a number of sub-properties (Pfohl 1990, Coyle et al 1996, Lumsden 1998, Stock and Lambert 2001): weight, volume, physical form, packaging, fragility, durability, and environmental sensitivity. The complexity of a product is reflected in its product structure, and has a direct impact on the logistics systems' configuration as well as the manufacturing system design. Product complexity influences the system management, and it is an important barrier to agility in the supply chain (Christopher 2000). Modularisation of complex products can rationalise the manufacturing and logistics system (Van Hoek et al. 1998). Product variety is an important parameter for choosing type of logistics strategy and hence the efficiency of logistics systems. Variety refers to both product variability and product mix, where variability refers to e.g. different models of a product. If product variety is high it is more difficult to reach economy of scale. The remedy is standardisation of products, modularization, material standardising and group technology (e.g. van Hoek et al. 1998). Finally, product value is an important parameter for manufacturing as well as for logistics although seldom taken as a design parameter. The value of a product is crucial in determining logistics strategy, as products of high value can carry larger costs than those of low value (Bowersox and Closs 1996, Pagh and Cooper 1998). Value can also be seen as added value for a customer, as is often discussed with a customer perspective, e.g. customer service, customer satisfaction (Cooper and Ellram 1993, Bowersox et al. 1999). Two product properties having direct influence on the customer's perceived value of a product are price and quality. A product of higher value offers more for the same price than another product, or, at the same price, brings more to the customer (Kotler 1988). The value of a product is to a large extent decided already by internal as well as internal product properties. For example, product structure influences the value added to the product, and the value of the material affects the cost-price equation, and thereby the profitability (value) of the product to the producer.

Research method

The empirical material originates from two case studies of EEE end-of-life management. Both studies adopted the case study approach, because it is appropriate for exploratory studies of complex phenomena and makes it possible to collect comprehensive, systematic, and in-depth information about each case of interest (Eisenhardt 1989; Patton, 1990; Merriam, 1994). EEE was selected as the area of study, because the implementation of the WEEE directive poses EU-wide challenges. The studies primarily involved Sweden-based companies, because the nation has been in the forefront of implementing end-of-life systems within the EU. Case A focused on product properties for efficient disassembly and involved computer screens and TV-sets, whereas Case B addressed efficient logistics systems for recycling of various types of EEE. As illustrated in figure 2, this paper addresses two crucial processes within end-of-life systems, i.e. the collection process and the pre-treatment process in terms of disassembly. Though end-of-life systems involve several different processes, the two processes addressed in this paper are vital for the operation of end-of-life systems in order to support further processing such as materials recycling or energy recovery.

Different data collection methods were used including interviews, on-site visits and observations, video recording, and studies of documents. Analysis of data was basically carried out according to the three-phase procedure outlined by Miles and Huberman (1994). In the first phase, interviews were transcribed and video-recorded material was studied and structured into logical sequences. In the second phase, case descriptions were written on the basis of the empirical material. The case descriptions were checked by the interviewees in order to enhance the validity. This is, as Yin (1993) argues, also a way of deepening the total understanding of the case studied. In the final phase, each case was analysed separately in order to extract the relevant product properties for efficient disassembly and end-of-life logistics. Thereafter these properties were compared and contrasted to each other and to extant literature.

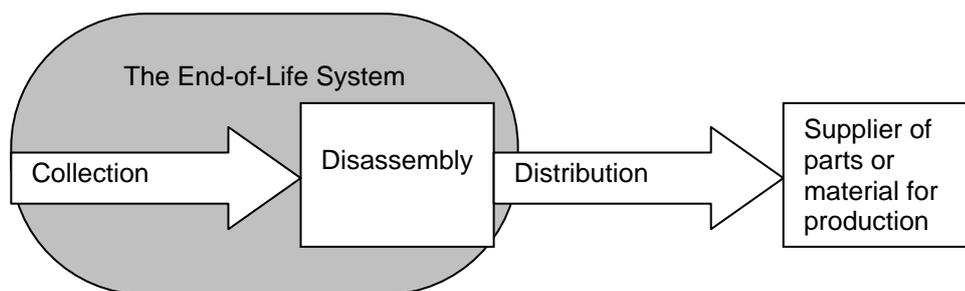


Figure 2: A simplified model of an end-of-life system with the recycler in focus, comprising the logistics of inbound flows from the point of product end-of-life, and the logistics of the outbound flow re-entering the products of the recycling process into the material flows. The shadowed area illustrates the two processes addressed in this paper.

Results

This section first presents the empirical findings and then follows an analysis of these findings.

Empirical findings

In our case studies we found nine different product properties important for performance of EEE end-of-life systems. Case A revealed four product properties that basically determine disassembly process performance:

- *Ease of identification*: The ease of identification property determines how easily a part (i.e. subassembly or component) that is to be disassembled can be identified, i.e. how easily the part can be recognised and how easy its location in the product can be found.
- *Accessibility*: The accessibility property determines how easy a part or a connector to be disassembled can be accessed.
- *Ease of separation*: The ease of separation property determines how easily a part or a connector can be separated from other parts of the product.
- *Ease of handling*: The ease of handling property determines how easily a part can be handled in the disassembly process. Handling refers to how easy it is to grasp and transfer various parts and connectors.

Case B revealed that the following product properties are vital for the collection process performance:

- *Fragility*: The fragility property refers to the risk that a component, sub-assembly or product is physically destroyed during the collection. High fragility indicates less efficiency in collection.
- *Durability*: The durability property relates to the possibility of long-time storage. A high durability promotes the possibility of long-time storage, which in turn promotes scale advantages in transportation during collection.
- *Complexity*: The complexity property concerns the physical appearance, number of and constellation of the component and sub-assemblies in a product.
- *Variety*: The variety property concerns the number of different product model and as well as the number of different product types (assortment). The higher variety the more diversified processes, and hence the fewer possibilities for efficient collection.
- *Value*: The value property refers to the inherent economic value of the product, sub-assemblies, components or materials.

Analysis

The product properties identified in the empirical studies can be classified according to three different product levels, i.e. the product assortment level (in this paper referring to both the corporate and family levels), the product structure level, and the component level (cf. Fabricius, 1994). The *ease-of-identification* property relates to all three levels. A precondition for the possibility of identifying a part (i.e. component or sub-assembly) is that it has a sorting feature, for example, magnetic properties or colour. Hence, the property is related to the location in the product structure as well as to the form, dimension and material of the part. Moreover, each product itself must be identified in order to establish which disassembly activities that are needed for that specific product. Therefore also the product assortment level is associated with this property. The *accessibility* property relates primarily to the product structure. The physical location, part orientation and hierarchical depth of the part in the

product determine how easily a component may be approached. The *ease-of-separation* property relates to two product levels. The interfaces between different parts affect how easily they can be separated, i.e. the component design influences this property. Furthermore, the number of separable, collision-free directions is essential and is set by the product structure. It can be argued that the *ease-of-handling* property relates to all three levels. The parts to be removed must be easy to grasp and transfer, which is associated with the component design in terms of form, dimensions and material, etc. Also the products must be easy to handle as regards orientation and fixation, i.e. the product structure is relevant. In addition, the number of different product variants that must be handled affects disassembly efficiency. This is related to the product assortment level. The *fragility* property concerns the product structure and component levels. The location of various parts in the product structure as well as the design of and use of materials in individual components affect this property. The robustness of each part is determined by its materials and surface, for example. This affects the possibility to refurbished and reuse the part in similar or other product applications. The product structure defines how easily worn out components can be replaced and hence the fragility property is also associated with the product structure. The *durability* property relates mainly to the component level and the assortment level. This property defines the possibility to reuse components as well as the time that they can be stored. Hence, durability refers both to the life-cycles of single components and durability in terms of materials ageing. The assortment level is mainly affected regarding the product life-cycle aspect in terms or reuse possibilities. The *complexity* property primarily concerns the product structure level. The number of parts and their locations determine the complexity of a product, and hence how easily the product can be handled within the collection system. The *variety* property is associated with the product structure level and the product assortment level. Different models of each product type may have different product structures, which makes the disassembly process more complex. Furthermore, a large variety of products makes the collection activities challenging which means that variety also concerns the product assortment level. The *value* property relates mainly to the component level. For example, the value of specific parts is associated with the use of precious materials or the recyclability of the materials. This determines the second-hand value of parts.

The above analysis regarding which product levels the different product properties relates to is summarised in figure 3. As can be seen from the figure, there are complex interrelationships between the product properties and the different product levels.

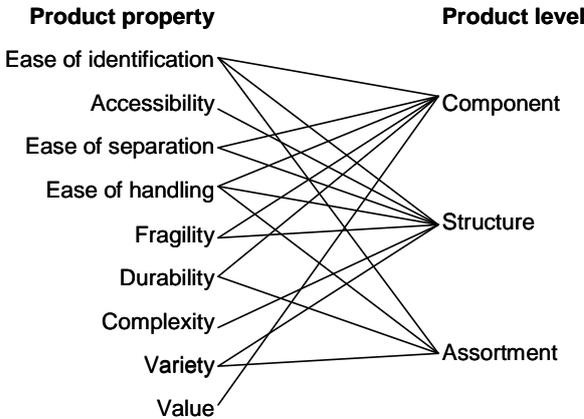


Figure 3: The identified product properties affecting end-of-life system performance and their relationships with different product levels.

The different product properties are not exclusively independent. Accessibility, for example, depends to a high degree of the product complexity. Furthermore, the ease of separation and fragility properties may actually counteract. Whereas high fragility is less favourable from a collection perspective, it may be positive from an ease of separation perspective in the disassembly process. For example, connectors that are fragile may easily be destroyed and hence allow for easy separation of different product parts. An idea that displays similarities to using fragility as a means to separate components is the concept of active disassembly (Suga and Hosoda, 2000; Chiodo et al, 2001; Chiodo and Boks, 2002; Hosoda et al, 2004; Hosoda and Suga, 2005). The underlying idea of the concept is that the use of “smart materials”, for example shape memory alloys (SMAs) and shape memory polymers (SMPs). Such materials undergo a specific change when exposed to an external trigger (e.g. increased temperature).

As was discussed earlier, all requirements set on a product as well as its internal and external properties are ultimately determined by the elementary design properties (Hubka and Eder, 1988). By establishing these elementary design properties, the product designers set the various product properties, including internal as well as external properties, and hence the degree to which the requirements are fulfilled. The various properties are set during the product development process when different product design solutions are developed, assessed and modified, eventually resulting in the final product. Basically, the elementary design properties also determine the product properties identified in this paper. Hence, choices made and decisions taken in the product development process affects the outcome in terms of efficiency in the collection and disassembly processes. In turn, the efficiency of the collection and disassembly processes has an essential impact on the overall end-of-life system performance. The relationships between in the product development activities and the end-of-life system performance as illustrated in the model shown in figure 4.

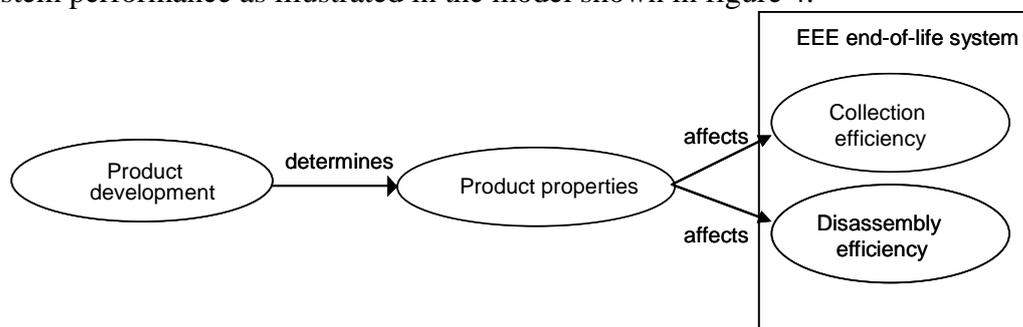


Figure 4: Relationships between the product development activities and the end-of-life system performance.

Strategies for developing products that support high end-of-life system performance

Research on “conventional” product development and logistics has resulted in insights regarding different approaches for achieving high manufacturing and logistics performance. Two such approaches are the application of modular product architectures and component standardisation (e.g. Ulrich and Tung, 1995; van Hoek, 1998; Herbertsson, 1999; van Hoek et al., 1999; Ulrich and Eppinger, 2008). The underlying rationale for establishing modular product architectures is to reduce variety of component and sub-assemblies, still offering a wide range of customised products. Modularisation is a product development strategy in which the interfaces between the sub-assemblies are standardised and specified to interchange of components and sub-assemblies across product variants (Mikkola, 2006). In the most modular architecture each functional element of the product is implemented by exactly one physical component or sub-assembly (Ulrich and Eppinger, 2008). The essence of modular

product architectures is hence to build a product based on a number of components and sub-assemblies that can be designed independently, but works together as a whole. Challenges associated with establishing modular product architectures concerns decisions on the appropriate degree of modularity, balancing different functional requirements in the modularisation process, and coordinating the modularisation process (Persson and Åhlström, 2006). Component standardisation refers to the use of the same component or sub-assemblies in multiple products (Ulrich, 1995). This allows for faster development of new products and increased manufacturing volumes of each component, which in turn results in greater learning and economies of scale, i.e. the unit cost decreases. Therefore sharing components across various product variants has been put forward as a sound way to capitalize on a company's investments in product development and increase efficiency in the value chain (Nobelius and Sundgren, 2002). Modular product architectures increase the possibility that a standard component will be commonly useful (Ulrich, 1995).

Application of modular product architectures and component standardisation seem also to have a potential to support some of the product properties outlined in this paper. If standard components are used to a high degree it supports ease of handling in the disassembly process. Similar as for assembly, special tools or equipment becomes less needed. Furthermore, standard components may also simplify the ease of separation because the number of different techniques used for joining these components may be reduced. Standard components and sub-assemblies may also affect the collection activities positively. Low variation of the products that are handled and stored enhances the possibilities to increase efficiency of the operations. Furthermore, less storage place needs to be reserved with a narrower assortment of components, and the management of the flows becomes less complex. If the product structure is based on modularisation principles, the accessibility may be positively affected. Also ease of separation should benefit from this approach. Modularization also enables a higher degree of efficient exchange of parts, thus prolonging the life of certain products (c.f. Clendenin, 1997).

Conclusions and Discussion

In this paper we argue that end-of-life system performance depends on a set of product properties that are defined in the product development process. Hence, product development is one of the main drivers of end-of-life system performance because a product's various properties are defined in the product development process. These product properties influence the disassembly process (as for the manufacturing and assembly processes in general) as well as the collection process (as for the distribution process in general). The findings are congruent with extant literature. That is, activities carried out and decisions taken in the product development process define the product properties, which in turn affect performance of subsequent stages of a product's life cycle (cf. Olesen, 1992). However, whereas previous research has indicated that this is the case also for end-of-life system performance this paper contributes with empirically based insights regarding which specific product properties affect performance.

It is obvious that the properties presented are interrelated in various ways. Further analysis into the interrelationships between the properties is therefore called for in order to result in a deepened understanding. Nevertheless, the findings presented in this paper indicate some practical and research implications. First, the implications for practitioners are that the findings provide strengthened arguments that modular product architectures and component standardisation are favourable approaches to apply in product development even though such

design strategies may also be associated with certain drawbacks. Complementary to the advantages for manufacturing and logistics likely end-of-life system performance will benefit from these design strategies. Second, the findings presented in this paper are based on two case studies only. Therefore it cannot be claimed that they are valid for other settings than those two cases. The proposed model describing the relationships between the choices made and decisions taken in the product development process and the end-of-life system performance is tentative. Additional studies are needed to validate the model and the product properties presented in this paper in order to develop enhanced understanding of which design strategies are suitable to apply during product development. Further understanding regarding when during the product development process the various properties are defined is also called for. The trade-offs between the various properties need more thorough attention, in order to provide managerial guidelines as well as more general knowledge.

The definition of the end-of-life system adopted in this study is limited. Only collection and disassembly processes have been included as representatives of the end-of-life system. Obviously, end-of-life systems include several other sub-processes such as refurbishing, fragmentation, sorting, etc. Further studies are needed to identify additional properties relevant for other sub-processes of the end-of-life system.

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