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New Demands on Design for Disassembly to Improve Recycling of Electrical and Electronical Products

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Abstract
This paper is a discussion of demands on disassembly of waste electronics and electrical equipment as a crucial prerequisite to enable actual recycling of materials and components. Disassembly is crucial to the amount and type of recycling of a product, and as such a standard concern of ecodesign, despite that it is not evident that ease of disassembly is equally relevant to the environmental impact of all kinds of products.

Although the recent WEEE directive places responsibility for waste handling and disassembly with the producer industry, it is still doubtful whether this induces ecodesign activities in the sector. On the basis of empirical investigations in the electrical and electronical industry the relevance of the design for disassembly approach to the electronics industry is discussed critically.

It is concluded that a deeper understanding of the conditions for the disassembly approach is needed to organize product development in an ecodesigned direction, which addresses both economic and environmental issues as well as issues specific to the technology such as the material complexity of products and the concrete possibilities of reusing major waste fractions such as plastics.

Keywords: ***WEEE, Ecodesign, Design for Disassembly, Re-use, Recycling***

1 Introduction
The WEEE (waste electrical and electronic equipment) directive does not meet its objectives of stimulating and improving ecodesign according to practices observed and to literature [1,2]. Applying new demands to the directive which force the companies to take a Design for Disassembly (DfD) approach is a possible way to improve the ecodesign in the industry.

The production volume of electrical and electronic equipment is growing rapidly and increases by up to 5% pr. year in Europe. Combined with a declining life-time of EEE products, the future need for optimised recycling is obvious [3,4].

The disassembly phase in an EEE product's life-cycle is crucial for the reuse of components and recycling of materials. Therefore, improving the design of WEEE products for disassembly seems to have great potential for optimised sorting, making it possible to separate components and materials, thereby improving the environmental effects of the products. However, with the development and possibilities in sorting technologies and recycling systems we have today, will a DfD approach also be relevant in the future and what should it be aimed at? This article critically investigates the justification and potential of DfD demands applied to the current WEEE directive. From empirical research results in the EEE and recycling industry goals and limitations of such demands are discussed.

Materials as plastics are an essential part in most WEEE products, its extensive use and possibilities for recycling makes it a material type which apparently would benefit from a DfD oriented product development in the industry. It is interesting to investigate if this is also feasible in practise, and therefore, this material type has been chosen as an example of the demands feasibility.

From empirical investigations in the recycling and EEE industry concerning the use of recycled materials and the use of the DfD approach, opportunities and limitations within these areas are investigated. This leads to a need for additional clarification and change of the WEEE directive where an environmental friendly product development is rewarded. Thereby giving an incentive for the companies to choose an ECO design strategy in the product development.

This article focuses on the design of future products, but the handling of these will be affected by the management of historical waste. The average lifetime of a WEEE product is 6 years, meaning that all the products we design today are treated in the future recycling system, causing a delay in the impact, if any, of a DfD approach. The mix of age of the recycled products and different scenarios of EOL, will also be a critical issue in the future. Therefore, the organisation and technical performance of the future recycling system is interesting and especially how these can affect EEE.

2 Methodology

Based on central points of criticism toward the WEEE directive, a discussion of new ecodesign incentives are opened.

The theoretical life-cycle of EEE designed for disassembly is described and compared to the practical implementation of WEEE, as experienced in investigations within the waste management sector in Denmark, leading to a prediction of the future recycling system and its potential. The investigations are based on interviews with 3 central actors within recycling of consumer waste, recycling of metals and recycling of industrial plastic waste [5,6,7].

The producers implementation, motivation and conditions for designing for disassembly are based on interviews and own experiences within two leading companies in the Danish electrical and electronical industry, Nilfisk Advance and Bang & Olufsen [8, 9, 10]. Nilfisk Advance produces quality cleaning machines for consumer as well as for professional use. The studied products in this case are vacuum cleaners designed for the consumer industry, a market where the technological development is limited and where Nilfisk Advance has a lot of experience. Bang & Olufsen produces high-end media appliances for the consumer market. Bang & Olufsen are represented in markets with high technological innovation rate, as e.g. the mobile phone market. The environmental responsibility today is an integrated part of high quality products as the ones produced by Nilfisk Advance and Bang & Olufsen. Their products are quality oriented and have a relatively long life time compared to other EEE of the same type, however, the majority of the products follow the typical EOL infrastructure.

The research data from the companies has been gathered via semi-structured interviews with the responsible within the field of environment and product development and from own work experiences with their products. Focus in all interviews has been on the companies' DfD experiences, environmental work practices, economical profitability and on the future of recycling and DfD. Based on own experiences within the companies, the data is evaluated as valid and reliable.

The identified practises of DfD and the limitations of improving ecodesign as seen from the producer's perspective are analysed with insights from the recyclers. The results from the interviews are compared to cases and research from literature within recycling, DfD and plastics, leading to a discussion on the future DfD approach and the critical factors for successful implementation and exploitation of new demands.

3 WEEE directive and the lack of ECO design incentive

The WEEE directive places product *end of life (EOL)* responsibility with the producers, meaning that companies producing or importing electrical and electronical products shall cover the economic expenses for the recovery of the products. With the shift in responsibility and the increased economic pressure, the WEEE-directive aimed at increasing the incentive for companies to lower their expenses by focusing on ecodesign and hereby increasing the possibility to recycle and reuse products [1].

The final directive was formed the 23rd of January 2003 after a period of investigations and reviews of the directives content [15]. The directive was enforced in 2006 in the European Union, but the WEEE directive does not prescribe exactly how the recycling system should be set up, therefore several implementation models exist among EU countries today [11]. In Denmark, public and private waste disposal companies are in charge of disassembly, material and component separation and recycling of EEE products, with no producer involvement at all. The way the recovery system is shaped today there are two key groups, the producers and the recovery companies, which are mutually dependent on each other. Seen from a stakeholders perspective it seems problematic that the producers, being primarily responsible, do not have the most influence and are not fully aware of their products properties during this phase. Furthermore, it also seems critical that the recovery companies have the same crucial knowledge and awareness about the products in the phase, but should have no say in the shaping and design of the products. Therefore, the producers position must be moved to a position as the real key actors with increased influence and awareness, so that the stakeholder with the greatest responsibility also has the greatest influence. The WEEE directive is the legislative framework to induce such changes.

Producers and importers must report the amount of electrical and electronical waste delivered every year. Using this information, the WEEE-system intends to map the recycled fraction, and thereby make every company responsible for the amount of waste they put into the system. The amount of waste is accounted for by weight, and current recycling percentages or ease of disassembly is not accounted for, thus making weight reduction the only beneficial aim for redesign. Measuring the reusability in terms of weight causes significant problems, because this value does not necessarily reflect what is environmentaly friendly, but is only a simple characterisation based on a lack of recycling knowledge. In this way, a notion of proportionality between weight and the impact on the environment has been established. Huisman et al. concluded that: *"Weight based recyclability targets of the WEEE directive are in too many cases leading to undesired eco-efficiency directions and in few cases even lower environmental performance."* [2].

This misleading evaluation method of the products must be changed in a direction that will give the companies an incentive for developing more environmental friendly products. Therefore, if DfD improves the environmental impact of a product, the ease of disassembly will be a better quantifiable parameter of a good ecodesign.

4 Environmental motivation

During the last two decades researchers have discussed DfD methods, and in literature several guidelines for DfD has been developed. Software tools have been made to improve products and to fulfill requirements arising from WEEE [11]. In general the tools for utilizing this DfX method are available and suited for the EEE industry. The critical points are the cost and resources necessary for implementing and using this approach in product development. Whether the expenditures of this approach in general are higher than in regular development is not unambiguous for the entire EEE industry, although classic examples as the Xerox Corporation's Asset Recycle Program have shown great economical sustainability.

While many other design methods directly benefit the company, e.g. in manufacturing and the assembly line, Design for Disassembly tools does not necessarily benefit the company [11]. Currently there is a lack of economical reward for implementing a DfD approach, and benefits will only arise from the combination of DfD with products oriented at reuse, having a modular platform or being a part of a product-service system.

The case has shown that when discussing the benefits of using a DfD method, there are different motivations which one has to differentiate between, which otherwise will lead to a flexible interpretation of the methods potential in eco-design. While products where modules can be replaced or serviced frequently throughout their life cycle have a more platform oriented structure and are easy to disassemble manually, products only aiming at low environmental impact can be difficult to disassemble manually because of limited access to joints. Instead these will be easily crushed into main parts when shredded or deconstructed in a similar process. These different directions must be taken into account in new demands rewarding reusability potential as well as the recyclability potential of a product.

5 Technology makes different conditions of DfD approach

The case study has shown that a good result within the field of DfD highly depends on the conditions of the technology.

Low product complexity makes the task easier to comprehend, while technology immaturity and high level of innovation affects the product in ways that make it harder to predict the architecture of the product and therefore also keeps focus on DfD. Consequently, the amount of resources used on this approach will be much larger, than for products with a relatively low rate of technological development. For instance, in the business of commercial vacuum cleaners which is characterized by low product complexity and slow technology development, the designers have good experience and a well established knowledge base, making it easier to optimize and prepare the product architecture to benefit the disassembly operations [8]. In contradiction to this, the development of a new high technology mobile phone requires the knowledge base to be developed continuously along with the product development. This leads to the statement that effective DfD cannot be combined with technology development projects, but is used for experience and knowledge development within the new product area.

Technological maturity, product complexity and innovation height are factors which is difficult to take into account when making a demand for easy disassembly. These factors could influence the products WEEE duty in a negative way, making high innovation products more expensive. That is the price of a better environment.

6 What can be recycled?

Modern technology provides great opportunities for designing a recycling system where the recycling percentages are close to 100%. Various shredding and crushing machines use hammers, cutting blades and rotary chains to efficiently crush the products fed into the system. Sorting machines use sensors such as colour cameras, magnets, eddy current and x-ray technology to sort materials by colour, conductivity and atomic mass with a very high purity leaving only very little for disposal waste [4]. Handheld scanners can also be used to determine for instance types of plastic, and ISO standard markings are used to inform the disassembly plant of material composition enabling the EEE to be divided into its smallest fractions [6].

Metals and alloys are in the highest grade of recyclable materials and the recyclability and eco-efficiency of these materials has not been doubted. A low grade material such as plastics are more controversial in terms of recyclability and eco-efficiency. The amount of plastic used in EEE products has increased along with the increase in volume of electrical and electronic equipment, which has drawn special attention from the plastic producers. During the last 15 years great effort has been made in investigating the recycling of plastics. Several authors have examined the potential of recycling plastic and determined critical factors in the sustainable recycling of the materials e.g. Dowie et al. and Dodbiba et. al [12,13]. Due to the versatile applications, the ease of complex moulding, low energy consuming processing and insulating properties, plastic materials will also be a significant part of EEE in the future. The use of plastics is increasing, and the use of plastic composite materials as a replacement for metal is becoming more and more common. The recyclability of plastic plays an important role, however it is important to clearly distinguish between the two types of recycled plastics which are on the market today.

Waste coming directly from the industry and collected by private companies are not to be compared with the recycled plastics from consumer WEEE. The uniformity of the plastics from industry is much higher because of the large fractions of one type of material. The purity and quality of the materials are therefore much better defined. Due to the relatively small amount compared to the number of suppliers, regenerated plastic often has limits within e.g. colouring.

The end-of-life possibilities for EEE plastics can be divided into four main categories. There are two types of recycling: Material recycling, also known as mechanical recycling, and feedstock recycling, a chemical recycling process. The last two categories are energy recovery and landfill. Research concerning the best potential use of resources compared to environmental impact has shown that mechanical recycling in general is more attractive than incineration, but that energy recovery in modern systems poses a clean alternative to average energy production [12].

Almost all plastics can be recycled, because the vast majority of plastics used in EEE are thermoplastics. With the different technologies that exist today the possibilities for recycling are potentially bigger than ever which will benefit the future recycling system [13]. It is stated that *"Feedstock can be the most eco-efficient and potentially the most sustainable strategy for managing a significant portion of plastics from today's EOL EEE"*, leaving confidence in the future of recycling of plastics [2].

7 The practical management of waste and recycling in Denmark

Across Europe there are great diversities in the management of waste, therefore the end-of-life strategies can be difficult to plan for the producers of future waste (new EE products). This poses two main scenarios of EOL which must be taken into account when making new demands to the WEEE directive.

The first scenario is recycling in countries with low wages for manual labour. The geographical final destination is the same for many of the materials, as most EE products are sent to Asia, primarily China, Taiwan and India [6]. Today 70% percent of the entire world's end-of-life electronics end up in China, either in shredded fractions or as sub assembled products. The recycling industry in Asian countries has grown, but in many cases not in an environmental sustainable way. With Chinese workers earning only 2$ a day, the amount of manual labour in China is much bigger compared to e.g. Europe [4]. Despite this first scenario of EOL for WEEE both are ethically and environmentally questionable, the world trade within waste will also be an issue in the future which must be taken into account, unless new legislative actions are initiated.

In this first scenario the waste treatment is primarily handled manually, for which reason a DfD approach aimed at manual disassembly will be a great advantage for the environment seen in a global perspective. New demands to the WEEE directive either have to accept this trade and formulate demands that initiate manually concerned DfD or make legislative regulations that keep the waste within European borders, where the handling are under controlled conditions. This leads to the second scenario.

The second scenario of EOL is complete handling within Europe, where the recycling industry is characterised by automation. Despite that the European recycling rate is below 30% great effort has been made, and the technology available today gives unique opportunities to get closer to the utopia of 100% recycling [4].

The supply of the largest possible fraction of EEE waste from the consumers is crucial for efficient recycling, and it is a well known problem that many household appliances will end in the bin together with household garbage and never reach a disassembly central. This accounts mainly for the smallest appliances leaving only larger appliances to the recycling industry. A further discussion of how to encourage consumers to use the recycling system and the effectiveness of the WEEE symbol are not in the scope of this article. It must be emphasised that consumers have a great responsibility in this matter and the lack of environmental responsibility also affects the product designer's motivation in thinking ecodesign, knowing that e.g. DfD efforts in these products are useless in the current situation, as there is no indication of change.

In Denmark, consumers deliver their WEEE in recycling stations across the country, from where private recycling companies pick up containers with WEEE driving it to a primary sorting station. Depending on WEEE classification the waste goes through a number of phases where the level of separation and material purity is increased. The disassembly and sorting of waste is a combination of manual handling, mechanical crushing and advanced sorting machinery. The manual handling primarily consist of moving materials and components described in annex II in the WEEE directive [14]. All non hazardous products are hammered and/or shredded to a desired size and under human while under supervision, taken through sorting machines. The advanced machines described earlier are an integrated part of the system, sorting into a very good quality leaving very little for disposal.

Plastics are in general sorted before entering the machinery by reading material marking symbols on the components and by generalising product type plastics. The end-products are fractions in hand size, where plastics are divided into types of various qualities. Whether the plastics are treated as plastics or as different types is a matter of sales price. The plastic industry sets the frame for the separation processes by stating quality and purity requirements to the recycled materials. It is only a matter of machinery programming to fulfil the demands, but refinement takes time and the technology is expensive. The sales prices reflect this, making it unattractive for the plastic industry to buy the relatively expensive lower quality materials [6]. The usable potential of these low quality materials is large and in other industries the materials are widely used as fillers in low quality products, and in products where the purity and material properties are of less importance. According to the recycling companies there is an unsatisfied demand for these materials [5,6,7].

Metals and glass have a much higher potential for reuse than plastics. The purity of all recycled materials is important when entering the recycling system, not only for the usability as recycled products but also in the previous step, in the recognition and separation processes. Clear marking of material type and high purity increases the speed of sorting, thus lowering the price with an increase in quality and usability. Therefore, rapid disassembly into well described material types is the key issue [6].

The disassembly centrals have been accused of not being designed for recycling, but only for removing hazardous materials [15]. In the practises observed, CRT screens and non RoHS compliant products are great expenses, especially in the early stages of the recycling process, which is manual labour intensive. In later stages of disassembly and separation great effort is made to ensure the recycling of materials and in Europe this is done with limited human handling. Today the disassembly central and the employee's ability to identify and remove environmental incriminating products are crucial to reduce the environmental impact. This however, requires a great knowledge across an enormous amount of products, it is very labour intensive and furthermore, the manual disassembly process takes time [6,7]. In the future, the decreasing amount of historical waste will result in extra resources, which can be used for optimised refinement of the automated sorting instead of manual disassembly. The time factor will also be critical for the economical profitability of the sorting and disassembly in the future. The critical products are the smaller WEEE products. High integration of components make them hard to disassemble, leading to low material purity, consequently the recycling usage benefits will not balance with the resources used to recycle them and the components may be better utilised for energy recovery [13]. Remarkably, it is the same types of products which today end up in household waste streams, typically in the shape of mobile phones and MP3 players, which in Denmark are utilised for energy production. A traditional DfD approach based on manual handling will in these types of products be of limited environmental benefit.

Despite automation effectiveness the case study has shown that some of the general design rules of the DfD approach still apply in the sorting and recycling system. Joints in the shape of glue and screws are the traitors in recyclability. Highly integrated products with a short life are also the main source of lowered quality and potential of the recycling system in the future [6]. Products consisting of several materials which are fused will therefore have a negative recyclability potential reducing the quality and potential of other recyclable materials, and thereby increasing the environmental impacts. Without these types of jointing and fusion materials, machinery will be able to crush and separate the materials without human interference [6]. This means that a DfD approach based on manual disassembly has very limited environmental effect in the automated recycling system, instead the disassembly in this EOL scenario should focus on separation of the materials through shredding.

When taking the technology available today into account and assuming that the discovery of new hazardous substances will decline in the future, the recycling system of the future will be able to handle all sorts of materials. It is very much a question of market forces; if the demand for pure materials is there, and it is economically attractive to use the recycled materials, the technology and manufacturers are ready. Despite the technological progress in the sorting and recycling area the scenario of global waste trade cannot be neglected. If restrictions are not made, the future products should therefore also aim at manual disassembly, and not only on separation of the materials through shredding which will be the case if the second scenario was the common EOL for WEEE.

8 Using and benchmarking the DfD approach

The handling of knowledge concerning DfD and storing it, is highly dependent on the market area and company profile. The age of technology is also reflected in the handling of this. In technologies with a steady development, the general guidelines for making a good ecodesign are often stored as tacit knowledge and as a set of norms in the company culture [8].

Other companies have a well described company manual for the development of products with a good environmental profile. Such a general manual to cover the entire product portfolio is seen at Bang & Olufsen [10]. The manual is based on an extensive research project with other EEE companies within life cycle assessments and ecodesign. This manual contains the legal prescriptions within the area, but also describes internal guidelines for material use, tools for disassembly, preferred jointing type and additives which are covered by law. The environmental department and technology manager are the stakeholders in managing this manual, and incorporating the demands in the requirements lists of products. It is important to stress that it is not a bonding codex and it is therefore flexible to new products which have difficulties meeting the requirements [10].

Disassembly of prototypes in cooperation with the disassembly central could be an optimal test scenario, and the case study shows that the companies conduct testing every time a new product types is launched [6,10]. In the case companies, the disassembly properties are currently not tested until the first 0-series, making it extremely hard and expensive to redesign the product even if severe problems occur. The testing is done by external companies leaving the designers with a written résumé instead of in depth knowledge about the disassembly process. Real practical insight has been requested by the designers, but not yet accommodated [9].

The scope of recycle thinking is in general offset to the product life phases from production to the possibility for separation of materials in the disposal phase. The usability of the recycled materials is not of concern to the product developers. Questions such as: *How can materials and components from our product be used in other products? How are the quality in the* *materials when reused and who are the potential purchasers of these?* are left to the manufacturers, recycling companies and the purchasers of recycled products. Making the products performance and functional unit more life-cycle oriented and thinking of possible secondary performances of the product are not common. Neither is cooperation between companies where waste is utilised for mutual benefit. In the industry, the theoretical potentials of utilisation of recycled materials are regarded as an idealistic vision, due to the diversity of EOL scenarios and materials. The companies rarely see controlled re-use or recycling between company partners as a realistic option.

Many of the metals used for production are recycled, but in general these are not seen as recycled by the EEE companies. When using the term recycled materials it is usually combined with low quality risks in use, for instance in the shape of recycled plastics. In the companies the knowledge within recyclable plastics is good, and internal goals are in general focused on not using PVC and flame retardants.

Despite the tendency to use conventional plastics, there is high awareness regarding the recyclability of the materials. The case study shows that the case study companies only use virgin materials in their plastic components [8,10]. The companies estimate that recycled plastics imply greater risk of low quality components due to e.g. surface imperfections and risk of quality issues in designs with narrow property ranges. The relatively small economic advantages of using recycled plastics are in most cases not attractive enough for the companies. For high-end products, as in the case of Bang & Olufsen, not even recycled material from their own industrial waste meets the demands of technology manager [10].

It is important to maintain the strategy throughout the entire development process and make sure that other dispositions do not over-rule the DfD strategy in order to harvest maximum benefits from the DfD approach. Both companies have made general considerations about DfD in their product development, but the company knowledge and DfD directions are only to a limited degree explicitly shared among the product developers. The case study shows that the companies focus on separating and labelling the materials without reusing or recycling the materials themselves. They have very little incentive to reduce the constructive freedom of the product, which a more holistic and comprehensive DfD approach inevitably will give.

If the magnitude of product changes and economic expenses become critical, it will be possible for the companies to deviate from the internal standards [10]. When this deviation is possible, the impact of such standards is reduced significantly. Instead of following own standards other companies use comparisons of their products environmental performance with their competitors, but an improved environmental profile at present is not a strong incentive for a market differentiation in EE industry.

With the lack of economic incentives for taking the DfD approach, another motivating factor is needed. In general the companies do not have any benchmarking of their products performance regarding DfD or other eco-design aspects. Therefore, it is difficult to make comparisons and common goals for the use of the method. Demands on ease of disassembly, either manually or by shredding will give a new eco indicator, a goal to aim at from the beginning of the product development process and a reason to make a more binding and explicit guideline within the producing companies.

9 Discussion and conclusion

The current possibilities in recycling technologies make it possible to recycle the vast majority of the materials used in EEE products. As the amount of historical waste decreases, economic resources will be released and can be allocated to a more detailed automated sorting, leading to higher quality of the end products leaving the recycling companies.

The case study shows that DfD guidelines on jointing and material use also have improved environmental effects in the future recycling system no matter what EOL scenario is used. Products designed for disassembly will improve the efficiency, but the different directions of the approach are not equally relevant in all recycling systems. The diversities in EOL of WEEE means that efforts on designing for manual disassembly in the future primarily will be benefit of the importers of waste, while products oriented at separation and shredding will be to the benefit of the automated systems. The future WEEE demands must therefore take these different EOL scenarios into account and reward both directions of DfD and thereby consider the environment in a global perspective unless legislative regulations are made in the waste trade area.

Today DfD methods need to be better adapted to the requirements of the waste recycling system. For the development of new demands to the WEEE directive, knowledge on how different products perform in current and future waste handling systems (manual, shredding) is needed, in order to allow waste recyclers to set up more relevant accounting methods compared to the simple weight amounts currently used. The new demands for evaluating design towards the environment must consider the environment and not recycling in particular, as the goal for all products which will result in a more holistic evaluation method.

The general understanding of DfD is good in the EEE industry, but the designers need more knowledge on the actual mechanics of the recycling system to determine all the critical DfD factors of products early in the product development process. The procedures in working with DfD in the EEE industry are informal or internal codified guidelines, but common for the investigated companies are the lack of benchmarking and the ability to deviate from internal standards in special cases. Demands in the WEEE directive in this direction will force the companies to take serious precautions on this matter.

The possibilities for good DfD design are related to the maturity of the technology and product innovation level. Because product experience is a critical factor an implementation of new demands to WEEE can result in an increase in the price on innovative products.

The use volume of industrial waste as well as WEEE recycled plastics is low in the EEE industry. The investigated companies estimate that the economic benefits do not compensate for the risk attached to this material type and the design requirements imposed by its use. The economic, technical and aesthetical aspects have greater importance to the companies. Therefore, to give the WEEE directive an influence on product development as originally intended, there is a need for new demands to the directive to induce this. Demands which draw the companies' attention to their products and where the developing companies are forced to manage the waste materials of their products. Demands on a quantified evaluation of the products regarding manually disassembly and by shredding can be justified. With these demands good environmental performances are economically rewarded in contraction to the existing weight based WEEE evaluation system.

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