INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

IDENTIFICATION OF COMMON STRATEGIES FOR DIFFERENT ELECTRIC AND ELECTRONIC EQUIPMENT IN ORDER TO OPTIMIZE THEIR END-OF-LIFE

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ABSTRACT

Regulation of responsibilities in end of life management has taken Design for Disassembly and Recycling (DfDR) into the spotlight, but conclusions and proposals for its application have been generated with a particular focus on individual products. General DfDR indications and strategies also exist, but their scope is so broad that they must necessarily be exposed in very conceptual and abstract terms. Analysis of such general strategies is therefore complicated.

This paper studies different products and the approaches generated in order to reduce their end-of-life environmental load. Three different electric and electronic product groups have been chosen. Differences can be stated as to their mechanical and electric or electronic complexity: inherently mechanical products, complex electro-mechanical products and inherently electric or electronic products.

The approaches to compare were selected after a thorough analysis of the possible disassembly sequences and the problems arisen throughout the process. Different design teams applied creativity techniques so as to generate improvement ideas, to avoid possible biases in the commonality of the proposals.

Although the proposed strategies tend to be different from one case to the other, common patterns arise, which make possible the generation of a list of universal approaches applicable to all products analyzed. Furthermore, important conclusions can be drawn from differences between the groups.

This paper is the first in a research line that will lead to a series of general ecodesign guidelines for particular families within the concept of electric and electronic household appliances.

Keywords: Design for Disassembly and Recycling, Waste Electric and Electronic Equipment, Ecodesign, End of Life Strategies.

1 INTRODUCTION

Although environmental consciousness of population has increased during the last years, the performance of companies in this topic has not followed at the same pace. Much effort have been given to process optimisation, Environmental Management Systems (EMS), and Best Available Techniques implementation, but introduction of environmental criteria in the development of industrial products has only been a reality on a small part of industry. Due to this context, policies have adopted an environmental point of view. Life-cycle issues such as packaging or waste have been included in recent legislation all along the world. In the case of Europe, a variety of Directives have been developed in order to influence the market behaviour. Obligations are determined for different stakeholders with the goal of attaining a better environmental performance of the market as a whole.

A topic that is given much attention within these is the optimisation of waste streams in order to reduce their environmental load. Regulation within Framework Directive on Waste 2006/12/EC [1] responds to this subject, including different Directives for each one of the major waste streams. One of the most important amongst these is Electric and Electronic Equipment, as is regarded in Directive 2002/96/EC on Waste Electric and Electronic Equipment [2], known as WEEE Directive. The

Electronics sector has not only presented a notable growth during the last decades, but also generates products with a prominently short technological cycle. Moreover, prices have been constantly decreasing. A conclusion of this is a naturally shorter life cycle, due to the fact that improved functionality in new equipment stimulates the customers to acquire the most up-to-date products. This constant renovation implies a problem when the products end their use phase, since the amount of waste generated is notorious.

The problem derived from this new and increasing waste stream is double. On one hand, much more land is needed for land filling than that available. On the other, some of the waste material contains highly hazardous substances that must be managed differently. Otherwise the environmental impact would be excessive in reference to international standards [3]. This problem is aggravated by the fact that no spontaneous market exists for the waste stream, as occurs with other kinds, i.e. glass waste. To address this, Directive 2002/96/EC defines a series of responsibilities for stakeholders involved along the product's life cycle. Producers must assure that their products attain a particular percentage of recycling and reuse, stated in the document, whilst distributors will aid in the inverse logistics process. Since economical responsibility of end-of-life management is transferred to manufacturing companies, they will have to assure that the minimums stated are feasible. For this, both end-of-life technology (shredding, recycling, disassembly, etc.) and new product designs must be developed. Next generation products must include amongst their specifications higher recyclability rates and easier disassembly sequences, to reduce end-of-life costs.

In order to address this issue, different products must be analyzed. For the purpose of this paper, three product typologies belonging to the category of electric and electronic equipment were selected, according to the degree of dependence of the product's main function to the mechanical or electronic complexity. Ecodesign Final Projects were then carried out in the School of Industrial Engineering of the Technical University of Valencia, with close supervision and collaboration from the members of the research group. For the most critical parts of the project, multi-expert teams were formed in order to breed feasible and consistent ideas. Members of these teams included students, the project tutor and other research fellows and experts in Ecodesign.

One of the main goals in each of these projects was to reduce the environmental and economical load at the products' end of life, adopting a holistic point of view. This paper will put together the improvement ideas generated in each of the brainstorms carried out during the development of the projects. Being these products so different, those approaches that are common in all projects will potentially be of appliance in general terms to all electric and electronic equipment.

2 DESIGN FOR DISASSEMBLY AND RECYCLING

Land use has received much attention lately due to its localized nature, adding to the fact that industrialized countries have seen their available land decrease considerably. Although this category does not necessarily represent one of the most severe environmental impacts, it is one of the most considered in European environmental legislation for this reason. One of the life cycle stages with most influence in this category is end-of-life, since the last action of most products has long been landfill, with the associated consequences. This waste quantity is to be reduced in order to avoid unnecessary impacts of this type.

On the other hand, raw material scarcity is in general terms a driving force for product recovery. The environmental benefits of product take back and further disassembly are obvious. Raw material extraction and processing is avoided, with the consequent impact on resource depletion, water consumption and energy use reduced. In some cases, these impacts have reached a level in which economy has acted as an additional driving force, for whichever of the previous reasons. In the case of waste management, landfill and incineration costs can drive recycling and reuse strategies as economically advantageous. Furthermore, high prices in some types of materials, i.e. steel, have generated a demand of recycled material. This has made some recycling businesses such as metal recycling fruitful.

When a product reaches its end-of-life, there are several ways in which it can be revalorised. Reuse of the product as a whole is largely considered as the most environmentally friendly strategy. The first Framework Directive on Waste included a further prioritisation of different operations for material recovery, which is shown in texts such as Directives 2002/96/EC [2] or 2000/53/EC [4]. This is coherent with most product's environmental performance [5, 6], since part reuse has for most cases a lower environmental load than, for example, recycling. This hierarchy is not systematically applicable

[7], i.e. some products might have greater impact if reused than if recycled. The new Framework Directive on Waste establishes a new hierarchy based on a three step approach [1], in which the decision about if a product should be recycled, incinerated or disassembled and used part-by-part, is left to the particularities of the sector.

In order to apply most of these strategies, the waste product must be previously disassembled. This is not necessarily the case with simple mono-material products, but it is definitely so with more complex electromechanical ones, such as those included in the category of electric and electronic equipment. For these products, this consideration must thus be included in the life cycle model, introducing either a manual or automatic disassembly stage, or a shredding process.

Products that reach their end-of-life nowadays have rarely included disassembly considerations in their design process. This represents a restriction for available possibilities to those given by the product structure and specifications oriented to service or maintenance. In some particular cases, this restriction forces a final shredding operation, since it is the only option that assures economic feasibility. Consequently, engineering design offers great potential for increasing the practicability of more environmentally conscious end-of-life processes.

Research on this field has taken recyclability into account for a long time, and more recently has included disassemblability amongst its considerations. Guidelines such as those included in [8] and [9] can be used in order to ease this final process. Moreover, more complex techniques have been developed aimed at evaluating up to which extent a design concept has a better or worse performance in its end-of-life. Numerous authors [10, 11, 12] have developed evaluation techniques at several levels with the aim of assessing the end-of-life performance and consequently be able to design in order to improve it. Tonnelier et al. [10] present an index that considers this performance at an initial conceptual level, by means of questions that are solved by experienced designers. Veerakamolmal and Gupta [11] also present a Design for Disassembly Index, which takes into account data from the disassembly process. Ardente et al. [12] introduce Global Recyclability Index, regarding different criteria in order to additionally include environmental, technological and economical factors in the model. Zussmann et al. [13] consider, on the other hand, that such recommendations are to be left to the designer’s experience and present a method to highlight which parts of the product should be addressed.

These techniques, however, require of a prior selection of the optimal end-of-life strategy. Should the product be recycled, reused or incinerated? The answer to this question strongly depends on factors that are not available at the initial phases of the design process, but in order to correctly design for disassembly and recycling, a decision must be taken. Rose [6] and Rose et al. [14] present a tool to systematically advice which end-of-life strategy is to be applied when the product reaches its end-of-life.

As can be seen, different tools have been developed to give the designer information about the product’s end-of-life performance. Either the tools give general information that is to be applied to whichever object or product-specific recommendations are spawned. It is possible to select the most suitable product alternatives for a particular product, i.e. an inkjet printer. Nevertheless, it is difficult to infer conclusions about general product families or typologies. A way to introduce this concept in the more fuzzy front-end phases of conceptual design would be to generate recommendations for groups of products, i.e. electric and electronic equipment.

As is shown in Figure 1, most DfDR techniques require information about the specific product studied, and therefore yield particularly valid conclusions for embodiment and detail design. On the other hand, at the top of the pyramid we find the design guidelines [8] for DfDR, which are suitable for every product. The middle stages of the figure, however, are not so clearly addressed in literature, due to natural difficulties.

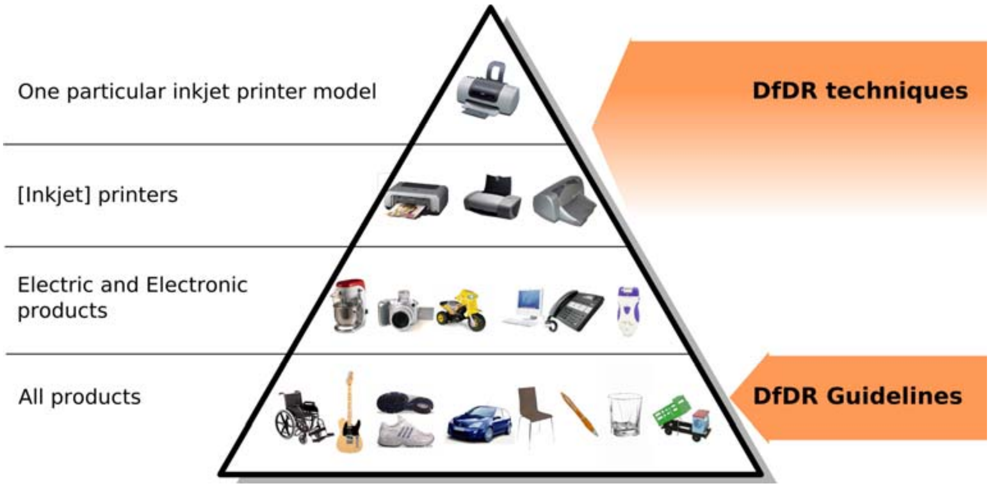


Figure 1. Approaches for defining DfDR recommendations

This paper will attempt to classify design ideas as to define a series of recommendations applicable to electric and electronic products in general.

3 PRODUCT DEFINITION

Electric and electronic equipment find a wide variety of different products within the term. They include such different concepts as TV sets or hairdryers. Appliances ranging from refrigerators to micro-sized MP3 players also fall under this category. This enormous diversity within the concept engenders a particular difficulty when analyzing this type of products as a whole. Such complexity has bred a well established classification in brown line, white line and grey line products. Industry lines up according to this classification, since each of the sub-categories is more coherent than the whole group. However, this division does not respond to functional or descriptive differences between the products themselves, since the similarity between, i.e., brown line audio systems and grey line audio peripherals grows more and more obvious. One of the most evident differences between products is their complexity. It is clear that “electric and electronic products” include relatively simple products such as a flashlight, but also complicated equipment such as a personal digital assistant (PDA). However, this complexity is not uniform in all levels of the product. Complex electronics can be easily combined with simple mechanical elements, i.e. in computers. On the other hand, some electric or electronic products are merely mechanical devices with a simple electric motor.

For the purpose of this paper, two types of individual complexity were established. The first one is mechanical complexity, taking into account the amount of physical dependencies and relative movement of the product’s parts. The second one would be electric or electronic complexity, related to the number of complex functions that the product is able to perform. Although the level of independence between both concepts is considerable, both terms are slightly related. Extreme levels of one type of complexity will always imply a minimum level of the other in order to attain basic functionality. In other words, very complex electronic systems will require of a minimum mechanical complexity to be operated, accessed, maintained, etc. Alternatively, in complex mechanical systems we find a tendency to automation, which is carried out with the aid of electronics.

While classifying a series of products according to their rating in these two variables, we find three common categories:

- Inherently mechanical products (IM), in which mechanical complexity of any level is found, but electronic complexity is reduced to a minimum number of elements, functions, etc. Even in the case of mechanical and electric or electronic simplicity, products are perceived as being mostly mechanical, so they will be considered in this category.
- Inherently electric or electronic products (IE), in which the mechanical part is limited to mere support for those electric or electronic functions that strictly require it.
- Complex electro-mechanical products (CEM). In this case, both types of complexity coexist.

In order to clarify this, Figure 2 represents these three groups in a graphical manner.

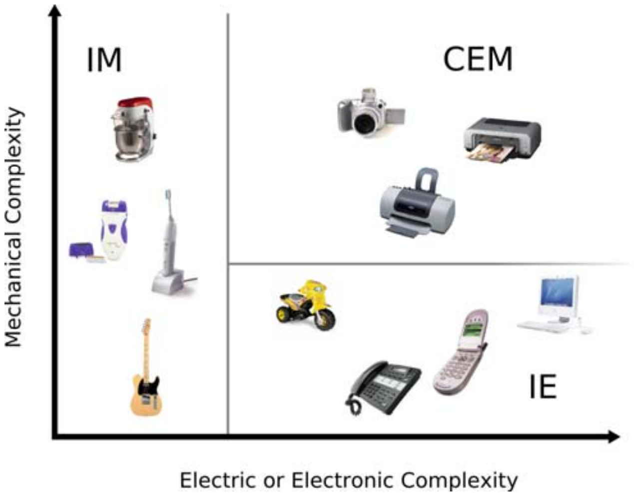


Figure 2. Product categorization according to mechanical and electric or electronic complexities

In Figure 2, each axis represents one of defined complexities. The level from which a product starts being complex in each one of the axis is left to the designer's perception, since the change in real terms is gradual. This categorisation will be employed in the following sections for the realisation of the study.

4 PROCEDURE DESCRIPTION

In representation of each of the groups exposed, several different products have been analyzed. The products have been chosen because of their differences in function and their household nature. These characteristics make them representative of most other electric or electronic equipment, since whichever selection is bound to be similar to any of them. Nevertheless, it must be noted that further research is to be carried out in order to increase the number of cases and to strengthen the conclusions derived from the experiments. The following table includes those considered in the study.

Table 1. Types of products analyzed for the study

IM	Electric Toothbrushes
	Irons
IE	Cordless telephone sets
CEM	Inkjet printers
	Scanners

Once determined, these products were completely disassembled and measured, in order to obtain the necessary information for redesign for disassembly. Information about the disassembly process was also gathered, including disassembly time for each part or module and the disassembly process' structure. Union types were recorded, as well as the necessary tools for each operation. Notes were taken along the process, so feedback was direct. Several redesign proposals came up during this phase of the study.

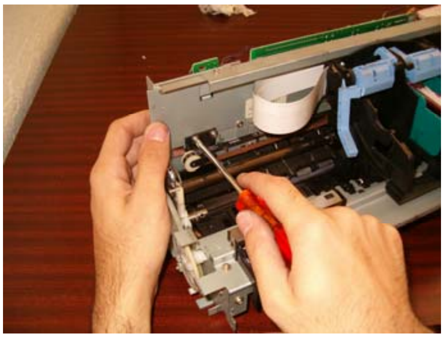


Figure 3. Disassembly Process

After the processing of the data, critical parts and problems were spotted and addressed by the project team of each of the products. This identification was done based in both the following criteria:

- Those that had to be extracted because of their weight or material.
- Those taking too much time to be extracted or those requiring the disassembly of several other parts before they are available.

Each team was conformed of a team leader directing the project, the students carrying out the disassembly process and the data analysis, in some cases an additional supervisor of the disassembly process and, when available, supplementary research fellows. Each type of product was undertaken in a different project by a different team. Nonetheless, team compositions were not fully independent, and some of the team members were involved in more than one team, especially in the leading and supervising roles.

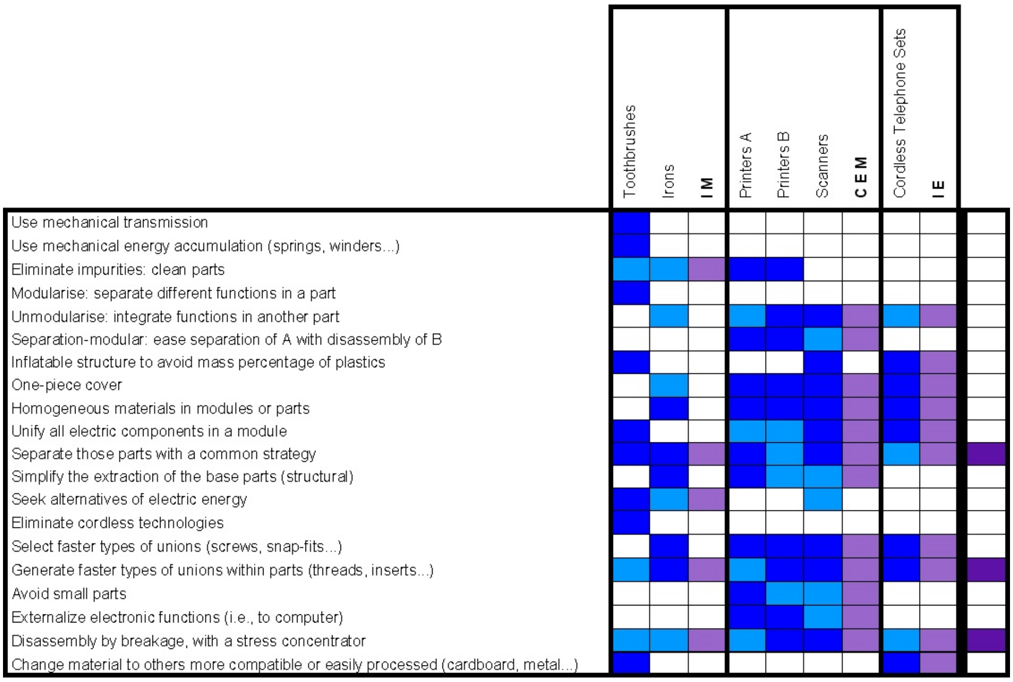
For each of the problems identified during the disassembly analysis, a brainstorm was performed. Large amounts of solutions were generated, and further filtering was needed. In the present study, all feasible ideas are considered. Some abstraction is relevant for harmonization, in order to properly compare very different products. Once these ideas are set, comparison between the different projects is carried out. The goal is to spot those that are applicable to all studied products within each of the categories considered. These ideas will entail a potential improvement for most products in the category. Furthermore commonality within the whole group of electric and electronic equipment is sought, subsequently allowing the definition of general guidelines for this particular type of product.

5 RESULTS OF THE EXPERIENCE

Comparison between all the products is shown in Figure 4. In this graph, alternative design improvement approaches are marked for each of the products. In the particular case of inkjet printers, two projects – each with different products – were carried out, so conclusions from both of them are exposed. The leftmost column shows all the general improvement approaches considered in the study. They were generated by abstraction of the improvement ideas that were spawned during the brainstorming sessions, in order to make them comparable from product to product, and thus avoid overlapping. Not all products have the same pieces, but they can have the same concepts behind them. These approaches range from classical strategies or recommendations such as the use of unions with easier disassembly (snap fits, inserts, screws, etc.) to more innovative ones such as one-part cover or disassembly by means of stress concentrators. The first one is applied with the aim of reducing the total number of operations needed, since cover parts are generally of necessary extraction. The second one is based on strongly reducing disassembly time, since a short number of impacts would be needed and some parts are bound to break along the process in any case.

Several different interpretations of product modularisation appear. Moreover, integrative approaches can also yield interesting results for some particular products. This issue is consequence of modularity not being such a well-established concept as it would initially seem. No universally accepted definition exists, since different authors interpret different variables [15, 16]. Apart from the function-based definition [9, 17], later approaches introduce maximum independence between modules as a key concept to measure the amount of modularity [18]. This breeds different strategies, since focus is set more on the interfaces than on the module functionality itself. Moreover, similarity between parts in the module [15] is also a variable that can be representative of this concept. The interpretation for this case would be to include all parts with a similar end-of-life treatment in a same module.

Dark blue cases imply that the approach came up directly during the brainstorm. Alternatively, light blue cases mean that the ideas would be compatible with the product type, although in the particular brainstorming session considered they didn’t appear. Cases for each of the categories are marked in purple if all products within the category can follow the approach to generate feasible ideas. In the IE category, only one type of product was considered: cordless telephone sets. Consequently, no commonality conclusions can be properly extracted for this category. The columns for this group will thus follow that of the product type. Nevertheless, its inclusion is justified to allow the comparison between the three different categories. The rightmost column is a compilation of approaches that were common to all three categories.



	Toothbrushes	Irons	**I M**	Printers A	Printers B	Scanners	**C E M**	Cordless Telephone Sets	**I E**	
Use mechanical transmission	🟦									
Use mechanical energy accumulation (springs, winders...)	🟦									
Eliminate impurities: clean parts	▨	▨	🟪	🟦	🟦					
Modularise: separate different functions in a part	🟦									
Unmodularise: integrate functions in another part		▨		▨	🟦	🟦	🟪	▨	🟪	
Separation-modular: ease separation of A with disassembly of B				🟦	🟦	▨	🟪			
Inflatable structure to avoid mass percentage of plastics	🟦					🟦		🟦	🟪	
One-piece cover		▨		🟦	🟦	🟦	🟪	🟦	🟪	
Homogeneous materials in modules or parts		🟦		🟦	🟦	🟦	🟪	🟦	🟪	
Unify all electric components in a module	🟦			▨	▨	🟦	🟪	🟦	🟪	
Separate those parts with a common strategy	🟦	🟦	🟪	🟦	▨	🟦	🟪	▨	🟪	■
Simplify the extraction of the base parts (structural)		🟦		🟦	▨	▨	🟪			
Seek alternatives of electric energy	🟦	▨	🟪			▨				
Eliminate cordless technologies	🟦									
Select faster types of unions (screws, snap-fits...)		🟦		🟦	🟦	🟦	🟪	🟦	🟪	
Generate faster types of unions within parts (threads, inserts...)	▨	🟦	🟪	▨	🟦	🟦	🟪	🟦	🟪	■
Avoid small parts				🟦	▨	▨	🟪			
Externalize electronic functions (i.e., to computer)				🟦	🟦	▨	🟪			
Disassembly by breakage, with a stress concentrator	▨	▨	🟪	▨	🟦	🟦	🟪	▨	🟪	■
Change material to others more compatible or easily processed (cardboard, metal...)	🟦							🟦	🟪	

Figure 4. Coincidences for approaches taken for different products

Results show that there is a considerable incompatibility between the groups, which yields a low number of common strategies (15% of the total). This is yet not the case within groups. CEM products present a uniform behaviour, with 85% to 95% of the feasible approaches being applicable to the whole category. A cause of this might be the fact that all analyzed products fall in the group of office computer peripherals. This gives them some commonality, although their general behaviour is considered to be sufficiently different to be representative.

IM products are not such a uniform group. Only 40 to 50% of the individual approaches are applicable in general terms to the whole category. An explanation of this can be the strong differences between the physical principles in which the product is based. Complexity in these terms is naturally bound to generate strongly differing approaches.

Special mention can be given to the amount of light blue cases in the graph. This is characteristic of the creative process and of the brainstorming technique: not all sessions will generate the whole space of ideas feasible. Different design teams take different approaches and develop different concepts. This effect, however, has been effectively compensated taking into account both types of cases: dark and light blue.

In the following section, the particularities that turned out in this study will be analyzed to gain proper knowledge of the common aspects.

6 DISCUSSION

As a general conclusion, one important common approach for all the products is to decide a strategy for each one of the blocks or modules inside the product. After this decision, it is the designer's goal to define a disassembly sequence and to design for the product to require a minimum number of disassembly steps. This definitely implies unifying those parts that have a common end-of-life treatment, separating them from the rest of the parts. This approach arises for all the products considered in the study, and therefore would be applicable for all electric and electronic equipment. If relative importance of electronic components is high, it would be convenient to unify all of these in order to extract them in a minimum number of steps. If it were the opposite, then materials unification is more relevant.

Another common strategy for all electric and electronic equipment is the generation of improved fastening techniques during part design. This would mean including elements such as threads, inserts, snap fits or friction unions that are part of the component. This generally requires much less time, and avoids additional parts and components when compared to other types of unions such as adhesives, screws, welding, and so on [8]. In some cases, it can also imply the avoidance of pollutants, be it by wear or by non disassembly. These elements would substitute others like adhesives, which have larges disassembly times, or even screws. This last option is not so time-consuming, but nevertheless implies additional materials being introduced in the products, sometimes unnecessarily. Snap fits would also fall into this category, even though they were also considered in another approach that ended up being not so extended as the previous: using already available unions with lower disassembly times. It is noteworthy that this other strategy did appear in almost all the product types, only not being present in the case of electric toothbrushes because of their common product topology.

An innovative approach that came up for printers and scanners, and was later considered to be applicable to all other products, is fast disassembly of the covers and fundamental modules by use of stress concentrators. An impact would be applied to the product in a controlled part, and mechanical energy would be enough to separate the needed parts. This can be considered for each individual module – one impact for each – or for the whole product.

Another perceptible conclusion is the difference between IM category and the other two. The first one is characterised by a strong disparity amongst the two cases considered, whilst in the latter we can find a strong homogeneity. As was commented in the results, approaches generated for IM products only found commonality in 40%-50% of the cases. One of the major causes of this is the diversity in the physical principles that rule each product. In the case of irons, most complexity is derived from the thermodynamic activities that occur for the product’s use. In the case of electric toothbrushes, the basis would be set in strictly mechanical movements. As can be seen, there is great divergence in the basic understanding of the product and, consequently, solution principles will be different to a certain extent. Moreover, in IM products there is not a common priority as to the parts and issues to be addressed, as happens with those products that have electronic components. CEM and IE products have in common that one of the problems to address is specifically the extraction of electronic components. Therefore, coincidence is less likely to appear in IM products. Finally, another point that influences in low commonality is the fact that IM category has a broader definition. It includes those products that are electrically simple, but also mechanically simple. This can provide divergence if the products selected are very different as to this.

Another particularity of IM products is the interest on avoiding material pollutants in the parts. This will ease the recycling process if selected as the convenient strategy. Wear of parts, inclusion of ink, metals oxidation, adhesives and contact with the user are some of the causes of the products pollution. The negative influence of these substances in the ulterior recycling process motivates this approach. Most of them can be associated with mechanical complexity, but not to electric or electronic complexity. This justifies not only IM products to follow this premise, but also the most mechanically complex product amongst those selected for CEM: inkjet printers. IE or highly electro-dependant CEM products rely on electronics, which is a technology that does not imply pollution of its parts.

A characteristic that arises in the CEM category is its robustness or homogeneity. Despite some particularly innovative or differing approaches, most of the ideas that were thrown in for inkjet printers could, almost unaltered, be applied to scanners. In this case, 85%-95% of feasible approaches for a particular type of CEM product were applicable to the whole category. This is empowered by the fact that both products are computer peripherals. Although conclusions are valid since very different functions are associated with the products, further study is proposed in order to extend these conclusions including contrasting CEM products.

No conclusions can be directly extracted from the IE category individually, but comparison with IM or CEM products yields an interesting result: cordless telephone sets behave in a very similar way to CEM products. Since in both cases one of the main priorities addressed was the electronic part of the product, results are coherent. More striking is the fact that, when electronic complexity is involved, it is one of the key factors that determine the approaches for redesign.

Particular mention must be given to the ways in which members of the design team brought up the concept of modularity. In some cases, it was associated with grouping together series of components in order to avoid disassembly steps. In these cases, modularity would be shockingly reduced if referring to the function-related definitions of this concept [17], but increased if analyzing more complex metrics [16]. This strategy was mostly proposed for CEM products. The cause of this is their complexity in both dimensions, since it entails that disassembly must be carried out at a module level and not at a component level. In other cases, integrative design was proposed in order to eliminate parts that were inconvenient or obstructive. Fundamental or structural parts should gather all these lost functions for the product to behave correctly. This approach is recommended for electronically complex products, no matter if mechanically simple or complex. In contrast with this, electric toothbrushes yielded a much differing approach. In this case, modularity was recommended, but in order to separate different functions in one single part. This way, reuse would become a feasible alternative, or parts that have a complex treatment because of their function would not imply large quantities of material being lost.

Mention can be give to the approach named “Seek alternative of electric energy”. For IM products, it is common sense that a way to avoid the problems derived from electric or electronic components is removing such parts. If energies other than electric are used, the product would no longer be electric or electronic equipment, and therefore would be removed from the present study. Opposed to this, CEM and EM products are heavily reliant on this type of energy. Therefore, such alternative is of very complex appliance, and can only be considered for specific parts of the product.

Concluding, within a group such as that of electric and electronic equipment, strong differences in the approaches taken in order to design for disassembly can appear. These differences are shown to be mostly dependant on the electronic complexity of the product, since mechanical complexity depends strongly on the working principles in which the product is based. Nevertheless, some strategies can be found for products with simple electric or electronic components. Furthermore, this paper shows that some common approaches or recommendations can be established for the complete group of electric and electronic equipment. Mainly, the objective of the designer must be to develop a strategy for the product’s parts to follow during the end-of-life phase. This way, the disassembly process can be decided and the design carried out accordingly.

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