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DESIGN FOR RECOVERY - APPLYING MULTIVARIATE STATISTICS TO DEFINE GROUPINGS OF FRENCH WEEE PRE-TREATMENT OPERATORS

Alonso Movilla, Natalia; Zwolinski, Peggy
University Grenoble Alpes, France

Abstract

Electronic appliances can follow different pre-treatment processes once they reach their end-of-use phase. To ensure their best recovery, their design has to meet the needs of the operators that are going to treat them. Design for Recovery methods have been largely developed in scientific literature for the last two decades. However, they are not properly adapted to the requirements of the different operators since they do not take into account the diversity of pre-treatment practices nor the reasons that lead to carrying them out. This paper first presents a qualitative analysis which allowed us to create a model containing the parameters that influence the functioning of French WEEE (Waste Electrical and Electronic Equipment) pre-treatment centres. Then multivariate statistical analysis has been used to define groupings of pre-treatment operators. Further work will focus on building the bridge between the identified groupings and ecodesign methodologies.

Keywords: Design for X (DfX), Ecodesign, Recovery, WEEE

Contact:
Natalia Alonso Movilla
University of Grenoble-Alpes
G-SCOP laboratory
France
Natalia.Alonso-Movilla@grenoble-inp.fr

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1 INTRODUCTION

Waste management strategies have gained a lot of interest all over the world for the last decades. Proper handling of products at the end of their use phase helps protecting the environment and human health, thus moving towards a sustainable life. The European Directive on WEEE (Waste Electrical and Electronic Equipment) (European Parliament and Council, 2003) has encouraged countries to establish recovery infrastructures, also known as compliance schemes or recovery networks, to ensure the collection and the correct treatment of this kind of waste. At the beginning WEEE recovery was mainly achieved by direct shredding of products. Despite the technological progress related to this process, secondary raw materials are often polluted. Disassembling products before shredding them provides purer raw material and offers new solutions for their recovery such as reuse or remanufacturing (Haoues, 2006). A wide range of e-waste pre-treatment centres, also known as operators, exists nowadays. Figure 1 shows the main steps a product undergoes in the WEEE recovery network. The first one is the collection and consolidation of products in different waste streams. The second one is the pre-treatment phase, which consists on the separation of a product into hazardous and/or valuable components and materials (Tanskanen, 2013). The last post-treatment phase allows output fractions to follow further final treatment corresponding to different recovery scenarios, that can go from reuse to landfill, through material recycling or energy recovery, according to the WEEELABEX classification model (WEEE Forum, 2013).

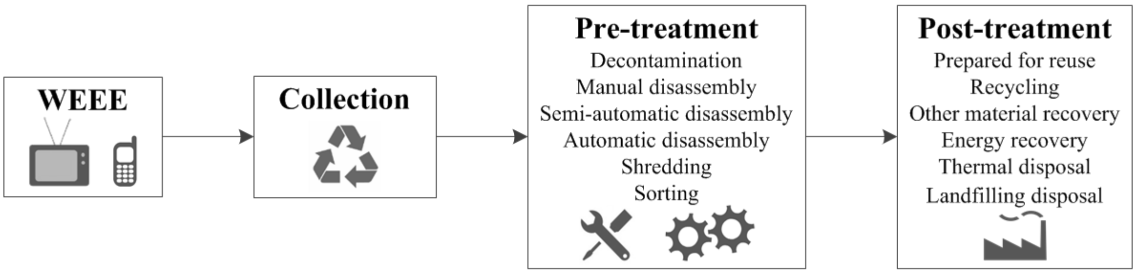

Figure 1. Main steps of the WEEE recovery network

Product design can render the different steps more or less efficient, especially the pre-treatment phase, which is the focus of our study. Indeed, the WEEE Directive, in addition to ensuring appropriate treatment of electronic waste, encourages manufacturers to promote the design of products in order to perform a more efficient recovery. However, designing a product to be properly recovered presents many challenges since it can be treated in different ways depending on the waste centre where it ends up. Designers should implement different requirements specific to the operators that will treat their products. But, what are the different categories of WEEE pre-treatment operators? And what are the parameters that define the type of operators who will recover a product?

2 RESEARCH METHODOLOGY

The aim of this paper is to divide into groupings the different WEEE operators that exist nowadays. We noticed that the different pre-treatment processes are being increasingly studied in literature (see section 4.1). Nonetheless, there is an absence of a deep study of the reasons that lead products to carry them out. This paper presents a model containing the parameters that induce products to be treated by one operator or another (section 4.2). The model allows increasing the level of understanding of the expertise of the different pre-treatment operators. In order to develop the model we have carried out qualitative analysis of the French WEEE centres. We have made several assumptions about the relationship between pre-treatment processes and the identified parameters. We have realised multivariate statistical analysis using data about French WEEE pre-treatment centres of the year 2012 to verify those hypotheses and to stablish possible categories of pre-treatment centres (section 5). The groupings should represent the diversity of pre-treatment operators. Further detailed analysis of the different groupings would help better understand what they needs are so that they can be translated into design requirements.

3 STATE OF THE ART

Recovery can be defined as the process of obtaining valuable products, components or materials from waste. To support the integration of recovery requirements during the product design phase, researchers have developed different methods and guidelines that are commonly found in literature under the name of Design for End-of-Life or Design for Recovery (Doyle *et al.*, 2011; Kwak and Kim, 2011). As shown in Figure 1, recovery encompasses a large number of different treatments. Some design methods focus on improving one single process like disassembly (Design for Disassembly) or recycling (Design for Recycling). Others consider a combination of different processes and scenarios, which some authors name Recovery System-Conscious Design (RSCD) (Mathieux *et al.*, 2008). The following subsections explore our preliminary literature review on Design for Recovery approaches that we have classified into four categories.

3.1 Methods based on guidelines

The first attempt to enhance product recovery was to develop design guidelines. Dowie and Simon (1994) developed Design for Disassembly and Recycling guidelines divided into 3 main categories: materials, fasteners and product structure. They pointed out that observations into recycling activities should be done regularly in order to keep the guidelines updated. Several universities and companies have carried out some studies in order to develop process-specific and prioritized guidelines accompanied by specific design strategies (Hultgren, 2012). A compilation of design for recovery guidelines for each WEEE stream has been published by French Producer Responsibility Organisations (PRO) (Froelich and Sulpice, 2013).

3.2 Methods based on disassembly assessment

Kroll and Hanft (1998) suggested evaluating factors like accessibility, positioning, force, tools or time in order to calculate the disassembly design effectiveness. Haoues (2006) proposed material, liaison and structure indicators that assess the conditions of recoverability, separability and accessibility. Gungor (2006) developed an analytic network process that allows designers to choose appropriate assemblies having into account all life cycle phases.

3.3 Methods based on obtaining recovery rates

Methods based on obtaining recovery rates aim at defining the suitability of a product to be recovered in terms of weight or in environmental terms. To mention a few: QWERTY (Huisman, 2003), ProdTect (Herrmann *et al.*, 2005), or ReSICLED (Mathieux *et al.*, 2008). These methods have encouraged the drafting of a technical report by the International Electrotechnical Commission (2012) in which calculation method for recyclability and recoverability rate is presented.

3.4 Methods based on optimizing recovery scenarios

Design for Recovery methods are increasingly integrated into more comprehensive approaches that aim not only at providing design guidelines, disassembly indicators or recovery rates, but at optimizing all recovery scenarios of products and their components. IREDA (Xing *et al.*, 2003) and MGE (Tchertchian *et al.*, 2013) methods allow designers to choose product characteristics based on recovery scenarios. LeanDfD (Favi *et al.*, 2012) methods evaluate the performance of several recovery scenarios like reuse, recycling, remanufacturing, incineration and landfilling, where disassembly parameters as cost or time are needed.

3.5 Discussion on the state of the art

The literature review conducted in parallel with the study of French WEEE pre-treatment operators shows us that the Design for Recovery methods presented above are not properly adapted to the requirements of pre-treatment operators. They are very general since they do not consider that recovery processes are not done the same way everywhere for the same product family. Most methods are very theoretical since they are very focused on product features and do not include external factors related to the organisation of the compliance scheme that highly influence the recovery process. We observe an evolution towards more comprehensive and complex methods which are gradually adapted to current treatment practices. This research work would like to contribute to such methods.

4 MODELLING THE WEEE PRE-TREATMENT PHASE

4.1 Existing pre-treatment processes

WEEE recovery processes are widely studied in literature. Handbooks on WEEE review them regularly (Goodship and Stevels, 2012). In France, the Environmental Protection Agency (ADEME) publishes an inventory of WEEE treatment plants every two years in which different treatments are described (ADEME, 2014a). Figure 2 shows our understanding of the different pre-treatment processes that WEEE can perform. They are not exclusive: a product can carry out several processes one after the other with intermediate sorting activities prior to post-treatment.

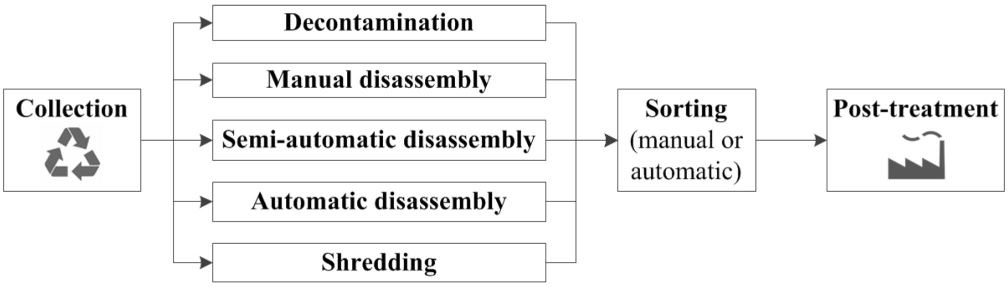

Figure 2. WEEE pre-treatment processes

A brief description of the five pre-treatment processes is provided below:

1. **Decontamination**: This process consists on removing hazardous substances that require selective treatment according to the WEEE Directive. One of the most representative decontamination processes is the extraction of cooling agents from old refrigerators.
2. **Manual disassembly**: It consists on operations that workers perform with hand tools. This kind of disassembly is the predominant practice (ADEME, 2014a; Duflou *et al.*, 2008). Manual disassembly can be destructive or non-destructive and reversible or non-reversible.
3. **Semi-automatic disassembly**: It is also called hybrid disassembly and it is a combination of manual and automated stations (Duflou *et al.*, 2008).
4. **Automatic disassembly**: This process takes place where all disassembly operations are fully automated. For most products it remains an academic goal, although we find this type of process in a French pre-treatment facility of Flat Panel Displays (FPD) (Veolia, 2014).
5. **Shredding**: It is a mechanical separation process in which products are inserted into machines that break or reduce them into different fractions. It can take place in the pre-treatment and in the post-treatment phase (WEEE Forum, 2014). During the pre-treatment phase it is called smashing or pre-crushing and products are opened so that workers can afterwards handpick hazardous substances. In the post-treatment phase products are reduced to smaller fractions that are automatically sorted.

4.2 Variables influencing pre-treatment processes

According to data from ADEME reports, the French compliance scheme has come to a stable situation in terms of quantity collected, number of operators and nature of treatment processes since 2011 (ADEME, 2014a, 2014b). These characteristics make it appropriate for us to study it in depth. The last inventory of treatment operators includes 196 plants that treated 460 800 tons of household waste and 108 000 tons of professional waste during the year 2012. A list of treatment operators is provided on the published directory (ADEME, 2014c) as well as on the online database Sinoe®. We have realised a qualitative study of the 196 centres through the following data collection methods:

- Reviewing online information (websites, reports, videos) of the different operators.
- Informal discussions with recyclers during the visit of 3 treatment plants.
- Informal discussions with e-waste experts at the Pollutec fair (2012 and 2013).

Numerous parameters have been found to have a direct influence on pre-treatment processes. We have classified them into 5 categories: organization characteristics, incoming products, pre-treatment processes, output fractions and context. The different variables, the link between them and our hypotheses on how they affect pre-treatment processes are explained in the following subsections.

4.2.1 *Organization characteristics*

- **Type of organisation**: Operators can be companies or association. Associations usually belong to the Social Solidarity Economy (SSE) sector whose purpose is giving a second life to products and components by reusing them. In this case manual disassembly is typically performed.
- **Relationship with Producer Responsibility Organisations (PROs)**: Most operators have contracts with PROs. This gives operators the possibility to invest on recycling equipment, and so carry out semi-automatic or automatic disassembly and mechanical treatment. Operators that have agreements with PROs to recycle e-waste material cannot separate products or components for reuse purpose. Only approved reuse centres can implement preparation for reuse activities.

4.2.2 *Incoming products*

- **WEEE stream**: WEEE ends up in different operators according to the stream to which they belong. In France there are 5 waste streams: Temperature Exchange Equipment (TEE), Large Equipment (LE), Small Equipment (SE), Screens and Lamps. Photovoltaic panels are a new stream from 2015. The stream Lamps is treated in the same way everywhere by direct shredding.
- **Type of use**: According to the users WEEE can be household (B2C[1]), professional (B2B[2]) or household equivalent (B2B with same product characteristics as household, like a personal computer). This classification has an influence on the collection channel (see next parameter).
- **Collection channel**: We believe the type of collection has a remarkable influence on the different pre-treatment processes. Figure 3 represents the different collection channels that exist.

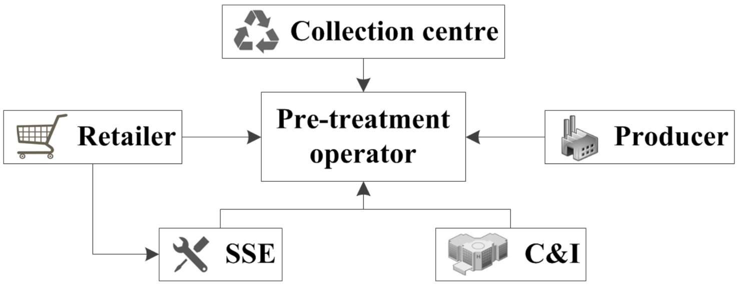

Figure 3. WEEE collection channels in France

  - Collection centre: WEEE disposed on collection centres is considered household and it is treated by operators that have contracts with PROs (see section 4.2.1).
  - Retailer: Household WEEE can also be disposed at retailers. They will then send them to operators that have contracts with PROs for recycling or to approved reuse centres as SSE.
  - Social Solidarity Economy (SSE): See section 4.2.1.
  - Commerce and Industry (C&I): Household equivalent appliances are treated by operators that have contracts with PROs since 2012. Before 2012 they were considered as professional equipment and C&I had direct contracts with pre-treatment operators. According to our researches equipment collected through C&I is more likely to be reused than the one collected through collection centres or retailer.
  - Producer: Sometimes WEEE is collected by producers since they provide services and not product, like domestic routers. Those producers have direct contracts with operators to treat their WEEE and recover valuable materials. This is a very interesting channel from a design point of view since recyclers and manufacturers can easily exchange information.
- **Content and type of hazardous components**: Hazardous components have to be separated for selective treatment. We distinguish 2 types, the first being *fragile hazardous components* such as Cold-Cathode Fluorescent Lamps (CCFL) from electronic displays. These components are manually dismantled since mechanical treatments are not appropriate. The other type is *tough hazardous components*, like capacitors from SE that allow pre-crushing for afterwards handpicking them. If there are no hazardous components mechanical processes are preferred.

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[1] B2C: Business to Consumer
[2] B2B: Business to Business.

- **Content of valuable materials**: WEEE with high valuable materials content is considered as urban mines. The ratio "quality/recovery time" is better when components are removed manually.
- **Data storage equipment**: Professional WEEE that is used to store confidential data is subject to specific data secure destruction processes.
- **Obsolescence**: Large obsolete equipment will not be recovered for reuse purposes even if they are still working. Products and components that are not outdated will be tested in order to see if they work or if they can be repaired. Designers should consider the rate at which the products are obsolete together with other parameters such as the product's lifespan (see section 4.2.5).

4.2.3 Pre-treatment processes

- **Process requirements**: Operators working with PROs have to achieve minimum recovery rates. Operators not working with PROs establish themselves internal requirements with usually higher target rates since they are able to reuse products and components. Sometimes the post-treatment centre fixes the requirements so that output fractions are treated in a proper way.
- **Quantity processed**: The more quantity processed the more likely it is to use semi-automatic or automatic disassembly or shredding. The same way, the less quantity the more manual disassembly and the most likely it is to carry on preparation for reuse operations.
- **Type of employees**: Many operators hire employees on professional insertion for no longer than 2 years, like SSE. Others hire people with some handicap. In both cases workers are principally asked to execute manual disassembly operations.
- **Treatment cost**: We make the hypothesis that treatment cost (measured in €/ton) has a link with the type of pre-treatment process and the quality of output fractions. This parameter doesn't suffer a lot of variations compared to recovery price (see 4.2.4).

4.2.4 Output fractions

- **Recovery scenario**: As shown in Figure 1 there are several possible recovery scenarios (post-treatments). Some scenarios require manual disassembly, like reuse or remanufacturing (in France). For the other recovery scenarios it depends on other parameters.
- **Recovery rates**: We believe that recycling and recovery rates have a correlation with pre-treatment processes. The higher the rates the less destructive the process is.
- **Recovery price**: The recovery price of output fractions is constantly changing. Operators have to adapt their processes and output fractions regularly depending on market circumstances.

4.2.5 Context

- **Production of WEEE**: This parameter depends on product's release date, end date, lifespan and amount put on the market. If the quantity of a particular product is growing, there is a chance that pre-treatment technologies will be developed (e.g. FPD). If, on the contrary, the production of WEEE is decreasing (e.g. Cathode Ray Tubes) there is also a chance that operators develop technologies to be more efficient in order to continue to work under PROs contracts.
- **Competition influence**: There are some WEEE streams in which there exists a lot of competition, like SE or screens. Processes in these streams can evolve easily. Other streams (LE, lamps and TEE) do not have so much competition, thus more stable processes can be expected.

5 MULTIVARIATE STATISTICAL ANALYSIS

We have carried out multivariate statistical analysis using data of French WEEE operators from the year 2012. The data has been collected by the French Environmental Protection Agency (ADEME). Collected data are confidential but ADEME agreed to share them with us for statistical purposes. From the identified 196 treatment plants, 169 have answered to the survey. Of these, 147 correctly reported the questions used in our study, resulting in a rate of 75% of the total. Operators are asked to provide information about the treatment processes they carry out for the different waste streams. They also specify the collection channels from which they got household and professional equipment. Table 1 shows the list of variables used for the analysis. All these variables are quantitative and are denominated in tons/year. Each of the variables does not match with one of the parameters described in the previous section, but they are a combination of two parameters. Table 2 explains the meaning of the variables' abbreviations and its relation to the parameters of the model described in section 4.2.

Table 1. List of quantitative variables used in the PCA (units: tons/year)

Name of the variables used in the statistical analysis				
TEE_ReuseProd	LE_ReuseProd	Screen_ReuseProd	SE_Manual	Operator_H
TEE_ReuseComp	LE_ReuseComp	Screen_ReuseComp	SE_Mecha1	Other_H
TEE_Manual	LE_Manual	Screen_Manual	SE_Mecha2	PRO_P
TEE_Mecha1	LE_Mecha1	SE_ReuseProd	Lamp_Mecha1	Operator_P
TEE_Mecha2	LE_Mecha2	SE_ReuseComp	PRO_H	Other_P

Table 2. Description of the variables' abbreviations and relation to model parameters

Abbreviation	**Description**	**Model parameter**
TEE	Temperature Exchange Equipment	WEEE stream
LE	Large Equipment	WEEE stream
Screen	Screens	WEEE stream
SE	Small Equipment	WEEE stream
Lamp	Lamps	WEEE stream
ReuseProd	Product reuse	Recovery scenario
ReuseComp	Component reuse	Recovery scenario
Manual	Manual disassembly	Pre-treatment process
Mecha1	Direct shredding	Pre-treatment process
Mecha2	Shredding after decontamination	Pre-treatment process
PRO	Producer Responsibility Organisation	Collection channel
Operator	WEEE operators	Collection channel
Other	Private individual, commerce or industry	Collection channel
H	Household	Type of use
P	Professional	Type of use

We would have been keen to obtain data on environmental parameters (recovery scenarios for output fractions and recovery rates) and economic parameters (treatment cost, recovery price) for each operator. Nevertheless, PROs collect this kind of information and they keep it confidential.
Next subsection presents the multivariate statistical analysis applied in order to better understand the link between the quantitative variables and to define the different groupings of WEEE pre-treatment operators. It has been realised using the program Statgraphics Centurion XVI.II.

5.1 Principal Components Analysis: Grouping WEEE pre-treatment operators

Principal Component Analysis (PCA) is a method for reducing the dimensionality of multivariate data sets (Mardia *et al.*, 1979). The purpose of PCA is to obtain a small number of linear combinations of the variables that account for most of the variability in the data. We have used it as a tool to group pre-treatment operators by finding relationships between the set of quantitative variables. In order to reduce the dimensionality of the data, several PCAs need to be performed. The first PCA starts with 147 cases (operators) and 25 variables. We have analysed the values of the three principal components for each operator and we have seen that four operators have important high values for one or several components. In order to obtain consistent results we have removed them for the next analyses. Subsequently, the second PCA uses 143 cases and 25 variables. This time some variables are linearly dependent. They are *TEE_ReuseProd* with *LE_ReuseProd* and *TEE_ReuseComp* with *LE_ReuseComp*. Their component weights (CW) are essentially the same for all principal components. We interpret that the reuse of LE and TEE (white goods) is carry out by the same operators. We remove then *TEE_ReuseProd* and *TEE_ReuseComp* for next PCA. Third PCA uses 143 operators and 23 variables and there is no more linear dependency between variables. We analyse the value of the variables' CW to detect the ones that account for the least amount of variance (below the mean). We identify 6 variables. The fourth and final PCA ends up with 143 operators and 17 variables. Figure 4 shows the CW for the first three principal components of this final PCA. They accumulate the highest percentage of the variance, accounting for 37% of the variability in the data set.

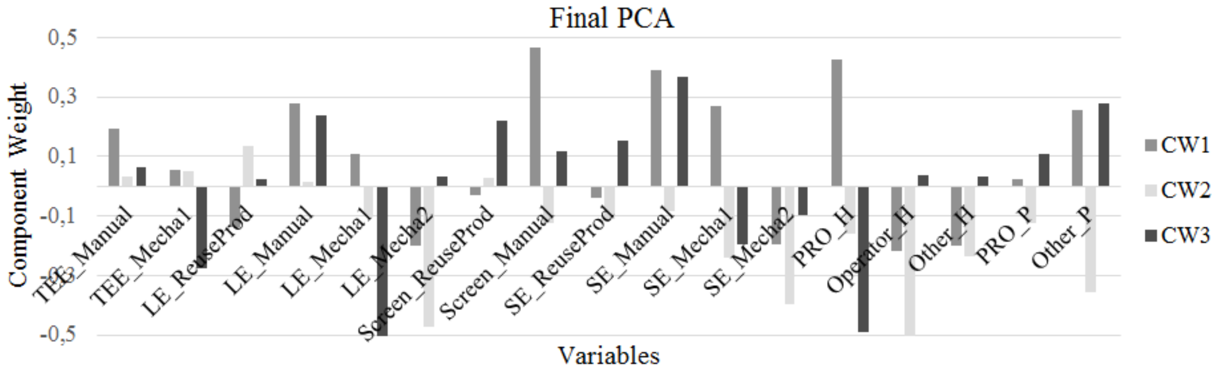

Figure 4. Component weights CW1, CW2 and CW3 for each variable

Component 1 (C1) has considerably positive weights for *TEE_Manual*, *LE_Manual*, *Screen_Manual*, *SE_Manual* and *PRO_H*. We can expect these streams to be dismantled manually when collected through PRO agreements. However, we also observe that Component 3 (C3) has negative weights for *TEE_Mecha1*, *LE_Mecha1* and *SE_Mecha1* and *PRO_H*. These streams are then likely to be mechanically treated when coming from PROs. This confirms our hypothesis (section 4.2.1) on how operators having contracts with PROs invest on machinery to carry out mechanical treatment. Screens, however, cannot follow any mechanical treatment because of their content on fragile hazardous substances. The difference between C1 and C3 is related to the treatment capacity. Mechanical treatment is done in larger quantities than manual disassembly, which is a logical result. C3 has larger positive weights for *LE_Manual*, *Screen_ReuseProd*, *SE_ReuseProd, SE_Manual* and *Other_P*. We interpret that the reuse and manual disassembly of "grey goods" (screens and SE) is related to the collection channel *Other_P*. This is a logical result that can be attributed to the renewal of IT equipment from C&I. We do not know how to interpret the high value of *LE_Manual* on C3 since we do not know the nature of the professional equipment that belongs to this waste stream. The negative weights effect of *LE_Mecha2*, *SE_Mecha2* on component 2 (C2) are associated with the negative weight of *Operator_H*. This is an expected result for LE since this kind of products are likely to be decontami-nated by one operator (who usually is in charge of the collection of WEEE) prior to be sent to another for mechanical treatment. As far as we are aware and according to PROs annual reports no transfer of SE is done between operators, so this is unexpected for SE. The information of the PCA can be translated into 5 main groupings or categories of WEEE pre-treatment processes (see Table 3).

Table 3.Main groupings of French WEEE pre-treatment operators

Category	WEEE Stream	Collection method	Type of use	Pre-treatment process or recovery scenario
1	TEE	Producer Responsibility Organisation	Household	Manual disassembly
	LE			
	SE			
	Screen			
2	TEE	Producer Responsibility Organisation	Household	Direct shredding
	LE			
	SE			
3	LE	Private individual, commerce or industry	Professional	Manual disassembly
	SE			
4	SE	Private individual, commerce or industry	Professional	Product reuse
	Screen			
5	TEE	Operator	Household	Shredding after decontamination
	LE			

Each of the groupings or categories is defined according to four types of parameters: the WEEE stream, the collection method, the type of use and the pre-treatment process or recovery scenario.

5.2 Discussion on the multivariate statistical analysis

PCA proved to be a comprehensive tool that allowed us to reduce the dimensions of the dataset and to explore patterns in our data. The results from the statistical analysis support and clarify our findings from the qualitative study. We can see in Table 2 that WEEE that is directly shredded is collected though PROs agreements, as we indicated in section 4.2.1. It is also demonstrated that reused equipment is likely to be professional, as we stated in section 4.2.2. Screens are not following any mechanical treatment due to their amount of *fragile hazardous components*. There were some results that we did not expect, like the professional LE coming from C&I that is manually disassembled. This equipment may make reference to large printing machines or computer-mainframes. Further research is needed to better characterise our model.

We have not been able to confirm our entire hypotheses due to a lack of data on other parameters that we identified in our model. We are also aware that our PCA explains only a small part of the overall variability of the dataset (37%). The database comprises very sparse information that does not allow obtaining better results. It would be desirable to realise the analysis not only with data from French operators but also with data from other European countries. This will allow us to have a larger perception of how WEEE is pre-treated in Europe.

As indicated in section 1, design requirements should address the needs of WEEE pre-treatment operators. Designers should then be able to know where their products will end up and what the characteristics of the different operators are. The descriptive qualitative study followed by the statistical analysis allowed us to identify different categories of operators according to different parameters. The inclusion of these categories in Design for Recovery methods will enable designers to adapt the design of their products to the specifications of the different operators. In addition, designers should ensure that the requirements help increase the durability of products since waste prevention should be the first priority of waste management (European Parliament and Council, 2008).

6 CONCLUSION AND FUTURE WORK

With this research work we wanted to overcome the lack of understanding of WEEE pre-treatment operators through the development of a (macroscopic) model containing the parameters that influence them. Multivariate statistics model PCA was used to give scientific evidence on how the different parameters are interrelated and to stablish the main groupings of French WEEE pre-treatment operators. Ongoing work is focused on the development of a microscopic model that allows studying in depth the activities of one kind of operator. This work is carried out together with the Joint Research Centre of the European Commission in order to develop disassembly and material efficiency related support for the Ecodesign Directive 2009/125/EC. Special attention is paid to the identification of product features that would improve WEEE pre-treatment practices. Further work will concentrate on implementing our model, the different groupings and specific design guidelines and recovery indicators in a complete Design for Recovery methodology.

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