GREENELEC:
PRODUCT DESIGN LINKED TO RECYCLING

Ruud Balkenende[1], Viviana Occhionorelli[2], Wesley van Meensel[3], Johan Felix[4], Sverker Sjölin[5], Maurice Aerts[6], Jaco Huisman[7], Julianna Becker[8], Antoinette van Schaik[9], Markus Reuter[10]

[1]Philips Research Eindhoven, Netherlands; [2]Barco, Kortrijk, Belgium; [3]IMEC, Leuven, Belgium; [4]CIT, Goteborg, Sweden; [5]Stena, Goteborg, Sweden; [6]Philips Lighting, Eindhoven, Netherlands; [7]TU Delft, Delft, Netherlands; [8]TNO, Delft, Netherlands; [9]MARAS, Den Haag, Netherlands, [10]Outotec Oyj/Aalto University, Helsinki, Finland

Abstract: GreenElec aims to significantly improve on the resource efficiency of electronics and electronic products. This is accomplished by close cooperation between manufacturers and recyclers. Design guidelines for improved recycling have been formulated and products (lamps and displays) have been redesigned according to these guidelines. Interestingly, design for recycling could easily be combined with value engineering. The improved recyclability has been validated in recycling runs. Further, tools are available to evaluate the choices made regarding materials and connections at various stages of the design process. As benefits are not evenly distributed over the value chain, business aspects are explicitly taken into account.

1. INTRODUCTION

As we create, design and manufacture globally increasing volumes of electronic products, the sustainability of scarce and critical resources for new electronic products as well as the treatment of electronic waste becomes critical. However, the notion of sustainability for electronics is at present mostly driven by energy efficiency during product manufacturing and product use. An efficient use of resources, including end-of-life recovery, only play a relatively small role and a significant percentage of electronics does not end up in the appropriate waste stream at all.

The main goal of the ENIAC project GreenElec is to significantly improve on resource efficiency of electronics. In close cooperation between manufacturers and recyclers, this is pursued by designing and manufacturing electronics that enable more effective recycling. In addition to technological aspects, business aspects are taken into account as the incentive for particular approaches can vary widely for different partners along the value chain..

The project aims for an efficient and sustainable use of electronic materials by delivering:

- Suitable combinations of materials for recycling.
- Design rules for electronics and electronic products taking into account recycling processes.
- Identification of recyclable/recoverable electronic devices and components.
- Methods and technology for sorting of discarded devices and components into well-defined waste streams.
- Optimum waste stream separation for maximal recovery.
- Business models and policy support that give an incentive to the recycling/reuse of electronics.

Three electronic product categories are used as case studies: LED lamps, consumer televisions and professional display systems. These products are analyzed with respect to their recyclability. Based on the obtained insights product redesign is carried out, followed by validation of the results in another round of recycling tests. Here an overview of the project is given, focusing on different aspects that enable improved recyclability.

2. KNOWLEDGE OF COMPOSITION

The composition of a product, but especially of the fragments that result after end-of-life treatment, determine to a large extent the potential recyclability. Although the recyclability of a material as such is important, the combination with other materials will determine its actual recycling potential. As an example, copper and aluminum can both be recycled

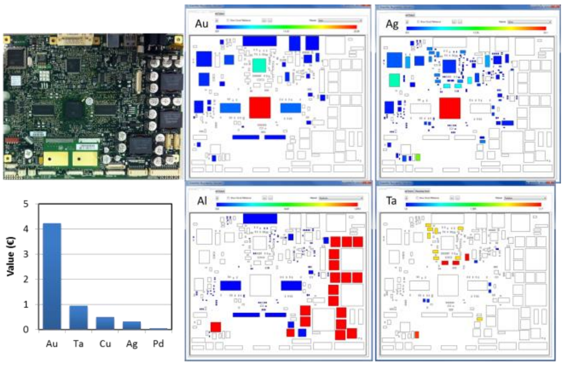

Figure 1 *Overview of PCBA in medical display and the mapping of elements present on that board.*

very efficiently, but when they are combined at least one of them is lost. This is due to their mutual incompatibility in the actual recovery processes (see next section for more details).

Detailed insight in the composition of products and likely recycling fragments enables calculations on the actual recovery under particular recycling conditions. For this purpose, full material declarations (FMDs) have been gathered for a large variety of electronic components. For a medical display a complete FMD for the PCBAs (printed circuit board assemblies) has been derived in this way. A database has been compiled that allows for easy insight in overall and local composition of PCBAs. The result, including mapping of amounts of specific materials on a PCBA, is shown in Figure 1.

Complete FMDs are difficult to acquire. To deal with incomplete FMD data, models have been developed that estimate the likely composition based on knowledge of the manufacturing process of components and the PCB lay-out. In this way those elements that are most important in recycling in terms of value and life cycle impact can be assessed.

The detailed knowledge on the composition can be used to optimize the choice of components with respect to recyclability, e.g. by clever distribution over multiple PCBAs. Insight in this information can further help recyclers in optimizing their fragmentation and separation procedures.

3. METALLURGICAL (IN)COMPATIBILITY

Recyclability of a product is often assessed by taking the weight fractions of the recyclable materials that are produced from pre-processing. This is an oversimplification as this approach not only neglects the collection rate (which to a large extent is beyond the scope of product design), but especially does not take into account that products are not separated in pure materials.

The actual recovery of especially metals takes place in metallurgical infrastructures and is a function of recyclate grade and composition. The recovery, losses and fugitive emissions in such processes are to a large extent dictated by the metallurgical technology as a function of the recyclate and particulate quality as achieved during pre-processes [1]. This determines the combinations of materials that can be recovered, will be lost or affect the overall process efficiency. This also largely influences the environmental impact of recycling, implying that considerable care should be taken when using LCA tools that mostly do not include this detail in their databases [2].

The mutual (in)compatibility of materials is shown in Figure 2 for a selection of the materials present in a LED lamp when reporting as economically valuable recyclates in different smelting infrastructures (see [2] for more detail). The extent of liberation of materials and the resulting quality of recyclates is hence critical for the actual recovery rates that can be achieved. Dependent on the metallurgical destination of the recyclates, which is affected by the recyclate composition, the actual recovery yield could decrease to zero for particular metals and anyhow usually requires different additions of "reagents" and slagging materials to

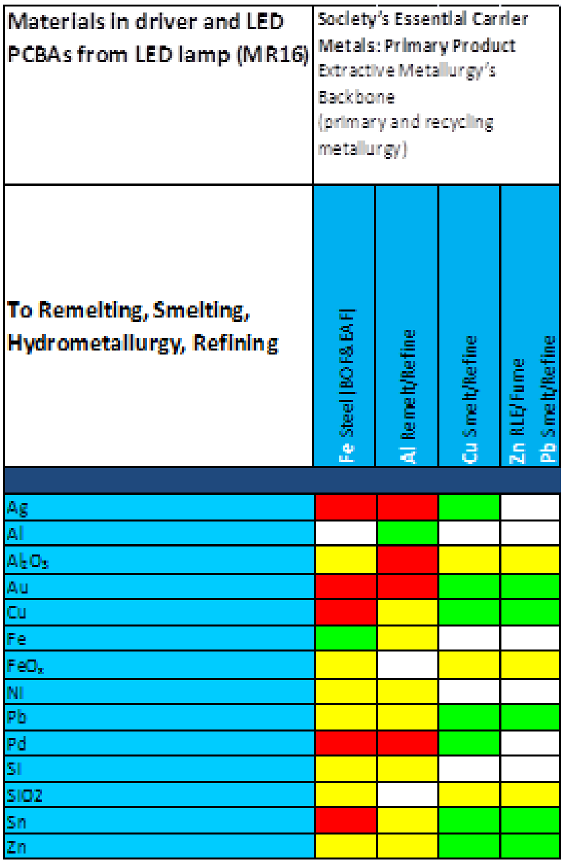

Figure 2 *Material (in)compatibility for materials in PCBAs of a LED lamp [1,2]*

optimize recovery, but incur costs.

As an example, if all fragments of the LED lamp after shredding would flow to the aluminum smelter, Ag, Au, Cu, Ni and Sn would basically be lost if not used as alloying element in the aluminum. Otherwise, if Ag and Au recovery are the objective aluminum will be lost.

Only rigorous models can truly evaluate the destination and recovery of elements as well as the impact of all processes due to all the residues created [3]. Therefore a detailed analysis of all streams, products, emissions, residues, etc. determine to what extent resource efficiency and closure of material cycles for both commodity and critical/minor elements can be optimized through design of products and technology recycling infrastructures.

4. RECYCLING TEST ON CARRIERS

A large batch of 'standard' LED lamps has been processed to obtain insight in optimal pre-processing (i.e. shredding) conditions and possible separation procedures. In addition, by studying the fragments that result from the shredding process fragmentation can be directly linked to various design aspects. By linking actual recycling behavior in this way to design features, design guidelines that take into account the way in which a product is likely to disintegrate at end of life have been derived. Figure 3 shows the resulting process lay-out for optimized recycling of LED lamps. Some results of the actual recycling run are shown in Figure 4.

Televisions and medical displays on average contain electronics that present a higher value than those in LED lamps. Mechanical disintegration is then not the optimal way to maximize the recovery of materials. In this case (partly) manual disassembly and separation turn out to be attractive. Figure 5 depicts the revenues as a function of the cost of manual disassembly (in Sweden). This shows that it is economically feasible to release at least half of the PCBAs manually. In addition, these experiments led to design directions that further facilitate manual disassembly of this type of electronic equipment.

5. DESIGN GUIDELINES FOR RECYCLING

Guidelines for Recycling have been set up that are based on actual recycling insights as described in Sections 3 and 4 as well as common design practices. The basic requirement for improved recyclability is to establish material streams. The guidelines distinguish between materials and connections and pay separate attention to the electronics themselves (the PCBA). They are depicted in Figure 6. Materials should be recyclable. Further, electronics is considered separately, as effective recycling routes exist for recovering many elements from complex electronic systems. However, even if recyclable materials are used, the way in which different materials are connected is crucial. An example is the screwed connection between a LED PCB and the heat sink. This causes that the aluminum heat sink cannot be separated effectively from the electronics, thus limiting the recyclability of both aluminum and electronics.

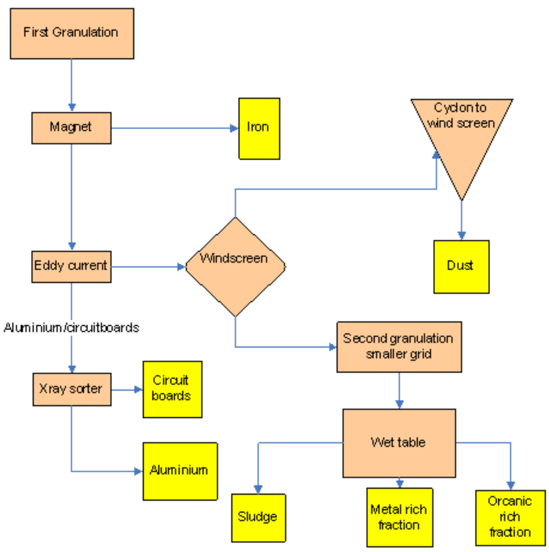

Figure 3 *Process lay-out for LED lamp shredding*

Figure 4 *Pictures showing LED lamps and material fractions from large scale pre-processing runs on LED lamps.*

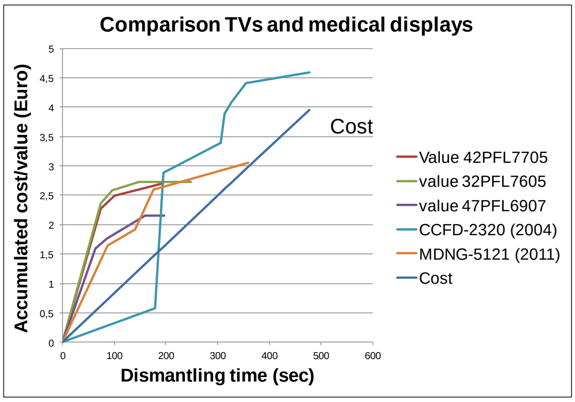

Figure 5 *The economics of manual dismantling of various displays.*

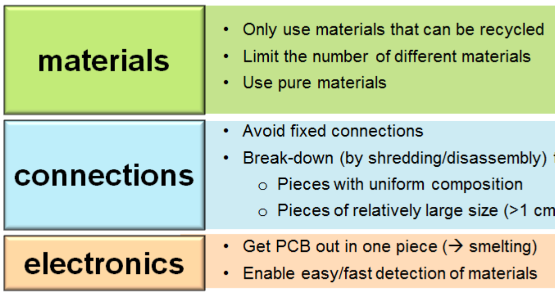

Figure 6 *Design guidelines for recycling focusing on materials use, the way in which parts are connected and the liberation of electronics.*

6. REDESIGNED PRODUCTS

Carrier products have been redesigned taking into account the design guidelines discussed above.

The Philips MR16 LED spot has been chosen as initial carrier for lamp redesign. Based on the design guidelines this lamps has been redesigned emphasizing different aspects of the design guidelines. An exploded view of a lamp made mainly of stacked deep-drawn aluminum is shown in Figure 7. In this lamp the deep-drawn aluminum parts replace parts made of engineering plastics and a die-casted aluminum heat sink. Further, all parts are simply stacked and only pressed together by a directly accessible ring at the top of the lamp. This lamp can therefore easily be disassembled manually.

However, LED lamps are relatively small electronic products that are most likely to finally end in a shredding process as described above (or into the waste bin). This should therefore also be taken into account in the lamp design. A small scale shredding test showed that the lamp is folded due to the high compliance of the thin Al parts. By introducing potting (sand or silicone, both easy to remove from the electronics and other parts) this could be prevented, resulting in excellent separation of the electronics when shredding the lamps.

7. RECYCLABILITY ASSESSMENT

The net environmental burden of recycling of a product depends on the one hand on the energy input in collection, separation and recovery, the loss of materials that end up in the wrong recovery stream, the limited yield of recovery processes as such and on the amount of recovered materials on the other hand. Especially the fragmentation of products during shredding is important as this to a large extent determines the effectiveness of separation processes.

This has been calculated for the redesigned MR16 described above assuming both the redesigned lamp with and without potting. As can be clearly seen from Figure 8 the lamp with potting has a much lower environmental burden than the lamp without. In the absence of potting the thin aluminum housing is

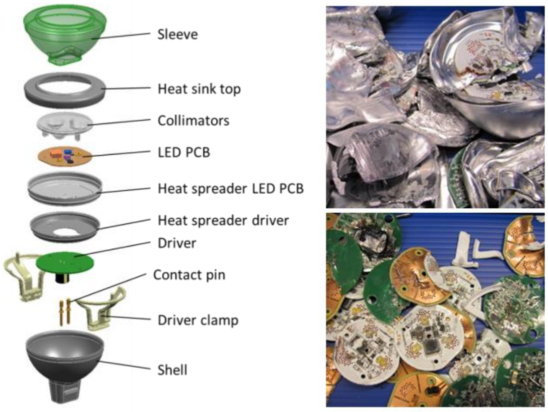

Figure 7 *Redesigned MR16 LED lamp made of stacked parts of deep-drawn aluminum. Recycling results are shown for the lamp without and with (sand) potting.*

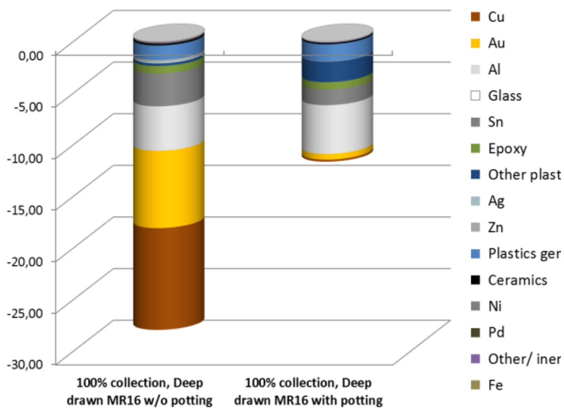

Figure 8 *Net environmental burden for recycling of the MR16 LED lamp shown in Figure 7 with and without potting.*

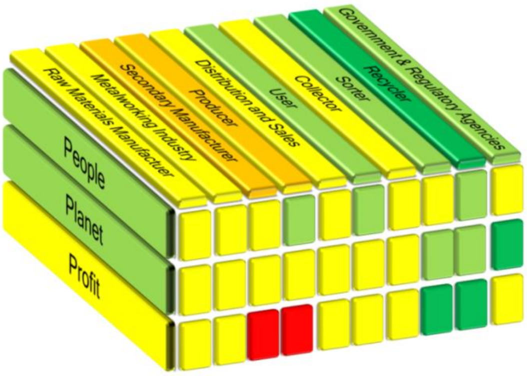

Figure 9 *Value case cube depicting the effect of knowledge of the complete composition of products for people, planet and profit from the perspective of different stakeholders.*

easily folded during shredding, thus enclosing the electronics that are then lost for actual recovery. The potting increases the stiffness of the lamp, leading to fracture of the housing and release of the electronics. However, in in a cradle to grave approach, the lamp without potting would score better, simply because less material is used [4]. Note that in this case either sand or silicone potting is used, that easily detaches from the PCBAs during shredding. If polyurethane potting would have been used, separation of the electronics into the appropriate materials stream would have been very difficult. This directly illustrates the key importance of already taking into account during the design stage the most likely treatment at end of life as the final fragmentation largely determines the possible recovery.

8. BUSINESS ASPECTS

The GreenElec project has identified possible areas of opportunities to achieve more efficient use of resources: materials and component selection, design and manufacturing, identification and sorting, waste treatment and materials recovery and impact quantification. Implementation of innovations in these areas is strongly dependent on specific stakeholders, but their impact is on the whole value network. Also the benefits of particular measures do often not coincide with the required effort, thus limiting the incentive to implement actual innovations.

In order to realize the goals of GreenElec and to successfully roll-out the innovations, interventions in the value network are therefore required. Possible interventions in the areas of business, government regulations, collaboration and society have been identified through in-depth value network analysis. Drivers and barriers, as well as the costs and benefits

Table 1 *Overview of intervention options for different stakeholders*

Business Interventions
Company level design guideline rules
Integrate recyclability indication into existing design software
Private scheme PRO
Government Regulations
100% recycling target with penalties for noncompliance
Standardization or specification
Suppliers must recover their own material
Arrange intellectual property rights
EU level design guidelines
Collaboration Interventions
EU level business case
Kick-back fee from recyclers to producers
Designers visit recycling plant
Courses for designers (assembly, disassembly)
Societal Interventions
NGOs organize consumers (increased collection)

insights were obtained in this way paired with the value case methodology. The methodology looks at complex stakeholder networks to pinpoint areas of opportunity to redistribute the benefits in the network and to provide incentives for all actors. This is illustrated in Figure 9. From this analysis, a list of potential interventions was made covering the aforementioned areas (Table 1). These interventions will be tested looking at their suitability, feasibility, and acceptability throughout the network. The results of this analysis will provide input to finalize and work out the interventions further to form concrete recommendations.

9. CONCLUSIONS

The GreenElec project has identified possible areas of opportunities to achieve more efficient use of resources: materials and component selection, design and manufacturing, identification and sorting, waste treatment and materials recovery and impact quantification. Implementation of innovations in these areas is strongly dependent on specific stakeholders, but their impact is on the whole value network. Also the benefits of particular measures do often not coincide with the required effort, thus limiting the incentive to implement actual innovations.

Possible interventions in the areas of business, government regulations, collaboration and society have been identified. Drivers and barriers, as well as the costs and benefits insights were obtained with the value case methodology. A list of potential interventions was made that will be tested looking at their suitability, feasibility, and acceptability throughout the network.

The research leading to these results has received funding from the ENIAC Joint Undertaking under grant agreement n° 296127.

10. REFERENCES

[1] M.A. Reuter and A. van Schaik, “Opportunities and Limits of recycling-A Dynamic-Model-Based Analysis”, *MRS Bulletin*, 37(4), 339-347, 2012

[2] A. van Schaik and M.A. Reuter (2014b). Product Centric Design for Recycling: Predicting Recycling Rates. An example on LED Lamp Recycling. To be published in *Proceedings Going Green - CARE INNOVATION 2014*, 2014

[3] A. van Schaik and M.A. Reuter, Chapter 22: Material-Centric (Aluminum and Copper) and Product-Centric (Cars, WEEE, TV, Lamps, Batteries, Catalysts) Recycling and DfR Rules. In: *Handbook of Recycling* (Eds. E. Worrel and M.A. Reuter), Elsevier, pp. 307-378, 2014

[4] J. Huisman, A.L.N. Stevels, Balancing design strategies and end-of-life processing, *EcoDesign 2003*, Japan, 2003