Heavy metals in consumer electronics recycling

Heavy metals in Consumer Electronics Recycling
A multidisciplinary approach

J.M.N. van Kasteren, P.P.A.J. van Schijndel, A.J. de Ron
Eindhoven University of Technology (TUE), PO Box 513, 5600 MB Eindhoven, The Netherlands, tel +31 40 2473024, email J.M.N.v.kasteren@tue.nl
A.L.N. Stevels
Delft University of Technology (TUD), Faculty OCP, Jaffalaan 9, 2628 BX Delft, The Netherlands, tel +31 15 2783027

Abstract

This study describes the heavy metal issues in consumer electronics recycling and a new way of solving these problems by starting a unique cooperation between designers, researchers and recycling experts of the Delft University of Technology (TUD), of the Eindhoven University of Technology (TUE) and electronic manufacturers as well as the recycling industry.
The production, use and discarding of consumer electronics contribute to the increase of heavy metals in the environment. By integral chain management the heavy metals burden for the environment can be minimized. This is only possible when there is a good synchronization and communication between product designers in the beginning and the recycling industry at the end of the product life cycle.

The project concept is that - based on the possibilities of recycling - product design can be modified such that heavy metal problems can be reduced or at least controlled. This can only be achieved if scientists from different disciplinary backgrounds cooperate in a single project. By forming a team of Ph.D.-students from different disciplines (chemical engineers, product designers and industrial engineers) which work together, the heavy metal problem will be tackled by a combination of prevention and end-of-pipe technologies. This will result in a better environmental performance and more economical use of resources.

First experiences of this cooperation have already resulted in a new way of dealing with the separation of the different materials during the end of life phase of consumer electronics. Part of the heavy metal issues can be tackled by focusing the research on the separation and upgrading of the heavy metal containing plastics involved from a perspective of the plastic reuse and therefore not focused solely on the heavy metals separation.

These experiences have shown that multidisciplinary cooperation is an excellent tool in order to foster the goals set by a sustainable development.

1. Introduction

Consumer electronics contribute in the end-of-life phase to the increased dispersion of heavy metals in the environment. These issues have to be tackled by integral chain management. This is possible if there is an optimal interlinkage between product design and recycling industry. It is the role of product design to find the compromise between purchasing, product design, production, functionality and ecological aspects. The present project aims to substantially improve on these issues.

Consumer electronics mainly consist of plastics, metals and glass. Dependent on the goal of handling waste and considering the minimization of the environmental impact for different type of materials, different treatments have to be performed. The present separation technologies used for the processing of consumer electronic waste are focused on maximizing the amount of reclaimable (heavy) metals, like iron (Fe), aluminum (Al) and copper (Cu), but does not specifically take into account control of the other metals like lead (Pb), cadmium (Cd) or zinc (Zn). This results in an unusable rest fraction which contains mostly polymers heavily polluted with heavy metals. Beside this, polymers contain themselves also heavy metals in the form of additives. They have been added to the polymers because of property improvements and processability. The rest fraction still causes the mayor part of the environmental burden of the recycling process of consumer electronics. The reuse of these waste streams will become more and more the key issue in the increasing eco-efficiency of the recycling of consumer electronics. A solution for the problem is also very desirable from a point of view of the optimal product design (saving materials and environment).
The Eindhoven University of Technology (TUE) and the Delft University of Technology (TUD) have decided to combine their expertise in this field in order to develop more efficient solutions for this problem. Therefore not only new separation techniques will have to be developed, but also the logistic possibilities and design limitations have to be taken into account. The reuse of the waste plastic stream would considerable improve the eco-efficiency of the recycling process and in that way open the avenues to reduce heavy metal leakage to the environment and also decreasing the environmental burden via the improved reuse of the plastic waste stream, thus reducing the amount of incineration and landfill. This means that closing the heavy metal cycle can be achieved by removing the greatest bottleneck via improving the reuse of the plastics in consumer electronics. This is the reason why this investigation is focused on the improvement of the recycling of the plastics in consumer electronics. This means not only separation of the plastics but also improving and developing its reuse in preferably new consumer electronics applications.

2. Take back and recycling of discarded consumer electronics

The most important phases in the life cycle of consumer electronics are:

design -> production -> use -> collection -> treatment -> recycling and waste treatment

In general the treatment of consumer electronics in the end-of-life phase is as shown in figure 1. This figure shows schematically that used product are first subjected to a selection of reusable products. These can be redirected to the market. Products, which are no longer reusable, are disassembled for reuse on component levels (e.g. certain chips or power units, which can be reused). Also most of the part with sufficient weight and purity are disassembled for recycling purposes as well as parts, which contain specific, credits. Presently disassembly is taking place manually which makes it very costly. Increasing application of mechanical processing and separation would make end of life treatment more economical, but should not be at the expense of the environmental performance. It is one of the basic aims of the current project to improve substantially the environmental gain/cost ratio of the mechanical processes. When this is no longer possible the products are grinded and the different materials are separated in order to recycle the materials like metals, glass, and plastics. Dependent on the input and the way the process is carried out, there rest waste fractions polluted with heavy metals.

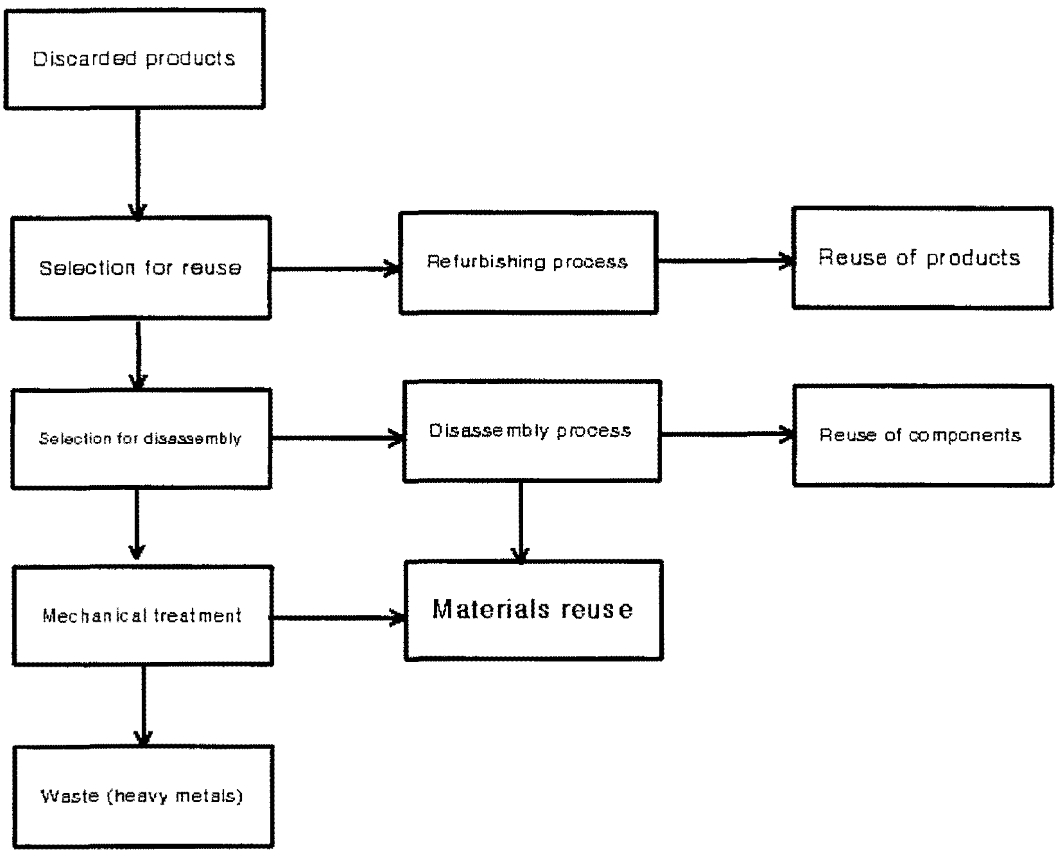

Figure 1. Schematic view of the recycling process of consumer electronics.

In this study the improvements of the recycling process will be measured in terms of eco-efficiency improvement. Th eco-efficiency of take back systems can be defined as the ratio of the environmental gain and the costs expressed in money to obtain this. The environmental gain can be expressed as the ratio of the amount of material actually recycled in unit of weight (kg) and the total weight of material involved. The costs are defined as the costs in money, which have to be made in order to recycle one kg of the material involved. These costs are based on the Dutch take back systems, which are currently operational (price level 1998). The general definition of eco-efficiency of the take back systems can be expressed in a formula as follows:

Eco-efficiency = Environmental gain/costs (money/kg)

This general eco-efficiency definition is worked out in two ways:

1. Eco-efficiency of recycling effectiveness, E(R).

$$E(R) = \sum(\text{Weights recycled} * WF/\text{weights}) / (\text{costs (money/kg)})$$

in which M represents materials and WF represents a material fraction

2. Eco-efficiency of heavy metal control, E(HMC)

E(HMC) = $\sum$((Weights HM controlled*T) / (total weight HM * T)) / (costs (money/kg))

in which HM represents one heavy metal
T represents the toxicity index, which is a measure of toxicity for a heavy metal based on toxicity data according to Nissen [Nissen, 1997].

Details of the calculation of E(R) and E(HMC) will be published in [Stevels, 1999]. The outcomes of the study will be an answer to the question whether improvements E(R) and E(HMC) will run parallel and if so to what extent. It is interesting to see whether replacement of a toxic material by an alternative less toxic material not only improves the eco-efficiency of heavy metal control (E(HMC)), but also the eco-efficiency of recycling effectiveness (E(R)). This outcome will give further clues how criteria for eco-efficient take back systems will have to be defined; this is in particular relevant in view of pending take back legislation in the EC countries.
Also for assessing designs, calculations of E(R) and E(HMC) for specific products will be of great help. In this way it can be established how far such products are situated from the average E(R) and E(HMC) of streams. This will allow selecting the candidates for product design.

3. The heavy metals issue

The problem of heavy metals plays in three categories

1. Control of potentially environmentally burdening heavy metals
2. Copper fractions, which emanate from the mechanical treatment
3. Mixed plastics which emanate from mechanical treatment

Copper smelters can process copper fractions from the electronic waste recyclers without problems. A number of heavy metals in this fraction like lead, antimony and cadmium can be reclaimed and reused. The plastics present in this copper rich fraction are burned in the copper smelters and their energy content is used. However, not all copper fractions can be recuperated in this way. Unfortunately, partly the copper and also other metals are present in the remaining plastic fraction, which is presently incinerated. Via this fraction part of the copper is lost and together with the other heavy metal contaminants is incorporated in the slag phase. This lowers the reusability and economic value of the incineration slags considerably (low eco-efficiency).
The wish to prevent such environmental problems is translated into new laws and strict legislation resulting e.g. in duty of reclamation and bans on landfill. This is why producers of consumer electronics are being confronted more and more with demands concerning recycling and reuse of their products. These demands must be met within an eco-efficient framework, thus stressing more and more the need of optimal product design. Via the design, producers have direct influence on the use of certain materials and combinations thereof and thus on the reprocessing costs. The wishes and possibilities of users and production units determine the design specifications for a product. Design demands, which account for the end-of-life phase,

must be incorporated as well:

1 secondary material stream properties have to comply with critical material specifications;
2 the technical and economical possibilities of the recycling industry;
3 the technical and economical possibilities of the collection systems and separation of different product streams;
4 functionality requirements of products can limit bulk recycling industry and metal smelters.

The demands of bulk recycling and smelters will be considered as starting points in this study.

4. The role of plastic recycling

Plastic recycling is complicated because of the many different types of plastics involved, which are difficult to separate from each other. Also different additives like flame retardants, plasticizers etc. have been added to the plastics thus resulting in a mixture of different plastics with many different additives (both from organic as from inorganic (heavy metals) sources). The existing physical separation techniques have limited capabilities and even if complete separation is possible the quality of an aged polymer will be less than that of a new virgin one. For less demanding applications reuse can still be very well possible. Because of the decreasing applicability in the reuse of polymers as function of its life cycle the economics become worse and worse; the value of the recycled materials decrease. This limits considerably the recycling of consumer electronics. A technological breakthrough is necessary to improve the recycling efficiency of plastics, both in separation and upgrading of the material as well as in material choice during product design and development. That is why the present project is not only focused on separation and reclaiming, but also on improving the quality of the used plastics via a method of modifying the polymers insuring that their material properties will be maintained and adjusted for applications. Through chemical modification of the plastic waste materials, materials will be produced with improved mechanical and physical properties.
For the determination of the technical and in particular the economical success of the recycling of consumer electronics the volume, composition and availability of streams are essential. Whether such streams are available depends on the type of collection systems and of the economy of scale at the recycler. These data depend on the collectors and the recyclers. Volume and composition of the product streams can be partially influenced. A considerable part of the project is focused on the logistics and process management, which integrates the complexity of the different phases in the life cycle. Optimization criteria are the environmental and the economical aspects.
When the possibilities of the new processing technologies are more clear as well as the volume, composition and availability of the waste streams, it is possible to use these experiences in the design phase to improve the environmental impact of the life cycle and to improve economical bottlenecks in the waste treatment systems.
The results of the project are especially of interest for the producers of consumer electronics, who can anticipate on their responsibility for the end-of-life phase of their products. Recyclers can use the results for optimizing their process and reusing also the fractions, which have been polluted with heavy metals.

5. The role of product design

From an environmental point of view the best way of tackling the heavy metal problem is to prevent that the heavy metals are present in the products. However, this is simpler said than done. Many of these materials have such excellent performance that their substitution and elimination is hardly possible, certainly not in the near future (e.g. copper). Besides this it will also be important to compare the life cycle performance between the heavy metals and the alternative materials.
As consumer electronics consist for the largest part out of plastics, metals and glass, contradictionary processing routes will have to be followed. These depend on the chosen recycling route and on the maximization of the eco-efficiency. This is also valid for the heavy metals, which are always present in certain concentrations in the different material streams. It is the role of product design to minimize ecotoxicity of the products. In order to determine which products are suitable for redesign, ecotoxicity calculations [Nissen, 1997] must be carried out for the products and the material streams. When certain products and material streams have been selected for redesign, it is still very important not to forget the life cycle perspective. This is in general the functionality (which can not always be realized without the use of heavy metals) and the relation functionality/price. A more intensive end-of-pipe treatment can be less expensive than the use of a very expensive alternative. It can be expected that the focus will be directed to the redesign of polymer/ heavy metal material combinations. In order to do this a certain stand of technique has to be taken. Before new design can be made, the following problems have to be addressed:

1. The present separation technologies used by the modern recycling plants are focused on the separation of the optimal mix of (heavy) metals, which can be reused. This results in an unusable rest fraction consisting mainly of plastics contaminated with heavy metals. This fraction still causes an important burden of the environment and further processing will become the economical bottleneck.
2. Plastics contain heavy metals themselves. These have been applied in order to improve certain properties such as flame retardancy (e.g. Sb) and stability (e.g. Pb).
3. The composition of the mix of metals determines the economical value. Some combinations are the cause of high penalties (e.g. copper should not contain Sb, As, Ni, Bi and Al). These combinations should be avoided.

From an environmental and from a designer's point of view the solution for the first two problems should be given priority. The reason for this is that designers should be given as much freedom as possible because they al ready have so many demands which they have to fulfil, in particular the product quality and performance during use. Therefore it is necessary to focus the cooperation between design and recycling on the problems of separation and reuse of the waste fractions, which are causing the highest environmental burden: the polymer fractions contaminated with heavy metals.

6. The role of operations management and logistics of the total recovery chain

Apart from the improvement of processes and the technology innovations for individual activities of the recovery process, as described in the foregoing projects, a further, and probably large, improvement can be obtained by considering the organizational, financial and environmental aspects of the total recovery chain.
The environmental friendly processing of discarded goods is located in the last part of the product chain. Until now, research with respect to optimal collection and processing strategies (in an economic sense or related to the recovery factor) has been directed to each single actor (collector, distributor, processor or smelter). Only the financial result of one single actor is optimized then (e.g. Penev and de Ron, 1996).
However, form a point of view of the environment and of society as a whole, the output of the total recovery chain in relation to the input goods has to be considered, where a multitude of quantities like recovery factor, eco-efficiency and reuse level have to be measured. Particularly it is important to see how the financial result of the actors in the total recovery chain changes compared to a financial optimization of the output of a single actor.

From practice it is known that by considering more actors of the recovery chain, other strategies will be developed than in the case of one particular actor only. This difference can be observed with easy recoverable and marketable materials, like ferro and non-ferro metals (e.g. Al, Cu). It is suspected that a significant different processing strategy will be the result for heavy metals and besides a financial optimization of the complete recovery chain will result in another collection strategy.
In the past research has been carried out concerning the logistic aspects of the recovery of products in their end-of-life phase. For the industrial and transport packaging industry Dubiel (1994) has identified three categories of reusable systems, divided into applications, and three organization structures. However, Dubiel views only costs and does not optimize in any way the financial and environmental aspects for the complete recovery chain.
Jahre (1994) has investigated the existing logistics chains for household waste in Europe. She has developed also a theoretical framework for the collection and processing of electronics products (Jahre and Flygansvaer, 1996). This framework is based on a process for the selection of distribution levels as has been described by Mallen (1970,1996). Mallen uses the following parameters in the logistics chain structure: the number of distribution levels, the number of actors, the type of actor and the number of logistic paths. The number of distribution levels concerns the number of operations that have to be done in order to get the used goods of the last user there, where the final recovery takes place. A consequence of fewer levels can be, for instance, that the transport costs will be high as a result of small volumes. A grouping may result in a reduction of these costs but increases the number of levels.
The number of actors per level concerns the number of collection points, the number of transporters and the number of processing facilities. The more actors per level, the more the selectivity can be.
The type of actor shows the functions that have to be fulfilled: sorting, storing, allocating and fragmenting. For instance, omitting sorting at the end user will increase the customer service as the end user does not have to do so much, but will result in more operations in the chain as the goods (or materials) are not sorted for the recovery process. However, the costs for transport and storage may be lower as the volume will be bigger.
The number of logistic paths regards to the question concerning the number of recovery systems to be installed. For instance, if one manufacturer of photocopiers has installed such a

system, what happens with the apparatus of other manufacturers?
Based upon the theoretical framework of Jahre and Mallen, in this project the logistic structures will be described in a more general form with the help of the four mentioned parameters. Important aspects will be:

- the involvement of each actor within the recovery chain and the influence of the chain structure thereupon;
- the functions of each actor and the value that is added to the chain;
- the number of different possible recovery chains and the reasons for the choice of the applied chains;
- the level of cooperation between the actors within the recovery chain.

The following two main goals will be the starting point of the research in the field of operations management and logistics that will be carried out:

1. the design of systems for operations management and logistics for the recovery chain of consumer electronics based upon optimization of these systems from environmental and financial point of view;

2. the translation of the conditions for these optimal systems for operational management and logistics into requirements for product design.

A model will be developed which describes the complex situation for the end-of-life phase of consumer electronics considering environmental and economical aspects of the complete recovery chain. The economical opportunities of the new developments in recycling as described previously will be determined. The optimization will be carried out by a multiple criteria analysis and different actors within the recovery chain will verify the results.

7. Short outline of the envisioned project

In this project the stand of technologies in the Netherlands will be taken as starting point. New developments during the project time will be incorporated into the project. Via calculations and modeling the product designs will be selected, which have insufficient control over heavy metals. Based thereon-new product designs will be made. Focus is given to the material streams, which are expected to cause a high environmental burden: the polymer fractions contaminated with heavy metals.
Investigations have started focused on a promising new development, which comprises the separation of the heavy metals from the polymer fraction and upgrading of the polymer fraction so that the polymer fraction can be reused. By improving the quality of the waste plastic streams the economical benefits from this stream can benefit the total process and make the recycling of the consumer electronics economically feasible.
By forming a team of Ph.D.-students from different disciplines (chemical engineers, product designers and industrial engineers) which cooperate and do research together, the heavy metal problem is tackled by a combination of prevention and end-of-pipe technologies, which results in a better environmental performance and more economical use of resources.
Refreshingly new is the cooperation of designers with recyclers in the research phase, both focusing on the same problems but from another background. This results in this original way

of looking at the heavy metal problem within consumer electronics. Therefore it is our belief that only by these kinds of cooperation a real step forward can be made in solving these difficult problems in accordance with a sustainable development.

8. Conclusions

1. The production, use and discarding of consumer electronics contribute to the increase of the dispersion of heavy metals in the environment. Integral chain management can minimize the heavy metals burden for the environment in an efficient way. This is only possible when there is a good synchronization and communication between product designers in the beginning and the recycling industry at the end of the product life cycle.

2. In order to reach a considerable improvement for the environmental performance concerning the heavy metals problem, a new project has been started which involves a cooperation between designers, researchers and recycling experts of the Delft University of Technology (TUD), the Eindhoven of Technology (TUE) and electronic manufacturers as well as the recycling industry.

3. The project concept is based on the possibilities of recycling; to modify product design such that heavy metal problems can be reduced and controlled. It is a necessary step for researchers from different disciplinary backgrounds to cooperate in a project which aims at decreasing the heavy metal problems in the secondary materials stream of consumer electronics recycling.

4. First experiences of this cooperation have already resulted in a new way of dealing with the separation of the different materials during the end of life phase of consumer electronics. Part of the heavy metal problem will be tackled by focusing the research on the separation and upgrading of the heavy metal containing plastics involved from a point of view of the plastic reuse and not focused solely on the heavy metals separation.

5. These experiences have shown that multidisciplinary cooperation is an excellent tool in order to foster the goals set by a sustainable development.

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