Nadja von Gries, Henning Wilts

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Nadja von Gries [a*], **Henning Wilts** [a]

Resource-efficient conception of waste electrical and electronic equipment collection groups

[a] Wuppertal Institute for Climate, Environment and Energy, Wuppertal, Germany

[*] Corresponding author: Nadja von Gries, Wuppertal Institute, Döppersberg 19,
42103 Wuppertal, Germany

E-Mail: nadja.von.gries@wupperinst.org

Tel.: +49 202 2492-139

Fax: +49 202 2492-138

Abstract:

Critical metals are in great demand by the electrical and electronics industry, so waste electrical and electronic equipment represents a significant source of secondary raw materials. Owing to low recycling rates and the concomitant supply risks associated with critical metals, the closure of the material cycles is highly relevant to the German economy. Losses of these metals occur from collection until their material recovery, along the entire disposal chain of waste electrical and electronic equipment. This paper develops planning criteria for the design of collection groups to achieve higher recovery amounts of such metals. The aim is to clarify what amounts of metals exist, both product-specific and on the market, how the dismantling of the products is constructed and how collection groups can be arranged with planning criteria oriented towards resource conservation. The analysis is a snapshot using the example of indium and selected products. A procedure is presented and findings identified which are transferable to various critical metals and to waste electrical and electronic equipment. The results show that grouping of products according to resource amounts and the dismantling effort enables forward-looking and resource-efficient planning of the treatment of every single collection group.

Keywords:
infrastructure planning, recycling & reuse of materials, waste management & disposal

1. Introduction

In 2010, an ad hoc working group under the aegis of the European Commission and in close cooperation with member states and stakeholders analysed access to a selection of 41 minerals and metals. The group identified 14 raw materials, mainly metals, of high importance for the European Union (EU) economy that indicated a high supply risk: antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals, rare earth, tantalum and tungsten (European Commission, 2010).

The limited availability of these metals can imply negative consequences in terms of the possibilities of producing and using new technologies. In particular, the growing market of environmental technologies, as well as the electrical and electronics sector, which maintains a sustainable energy supply and is aimed at information technology advancements, is dependent on a variety of these so-called critical metals (European Union, 2010). (Note that the term ‘critical metals’ as used in this paper comprises a group of metals which show demanding supply risks and economic relevance despite low metal volumes and low recognition in the past.)

Recycling of these critical materials can be an important part of the EU’s strategy to secure continued access to these metals. To follow this path will require a greater focus on the qualitative aspects of the recovery of metals (UNEP, 2013), because many of these critical metals are characterised by dissipative use, meaning that they are used in small amounts throughout a multitude of application areas or products. The existing recycling policy and infrastructure – the current forms of collection and recovery techniques – have not yet focused on this problem, which means that (thanks also to insufficient economic incentives) most of these critical metals are not recovered (UNEP, 2011).

Waste electrical and electronic equipment (WEEE) as one major field of application for these metals has become one of the fastest-growing fractions of municipal solid waste (UNU, 2007). Considering the multitude of actors and products, the rapid changes of technology, product design and related material composition, as well as its rather opaque life-cycle chains, WEEE is one of the most complex waste fractions. As a consequence of these continuous modifications of function and design of appliances, electrical and electronic equipment contains a highly heterogeneous mix of materials and essential constituents, much of which includes critical metals (Chancerel, 2010). The increasing complexity of computer chip technology highlights this development. In the 1980s, computer chips were made with a palette of 12 elemental components; a decade later, 16 elements were deployed (NRC, 2008). Today, as many as 60 different elements are used in fabricating integrated circuits (NRC, 2008).

A crucial aspect for improving the recovery rates of these critical metals is the composition of collection groups for WEEE. The existing composition is given by the WEEE directive (directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)) and distinguishes between ten product groups (EC, 2002). Most EU member states have chosen to collect in fewer groups; for example, in Germany, the groups are as follows

- Collection group 1: Large household appliances, automatic dispensers (categories 1, 10)
- Collection group 2: Refrigerators (category 1)
- Collection Group 3: IT and telecommunications equipment, consumer equipment devices (categories 3, 4)
- Collection Group 4: Gas discharge lamps (category 5)
- Collection Group 5: Small household appliances, lighting equipment, electrical and electronic tools, toys, sports and leisure equipment, medical devices, monitoring and control instruments (categories 2, 5, 6, 7, 8, 9)

The composition of these categories is based on very practical aspects such as handling, space requirements and content of hazardous substances or on recovery rates. In particular, collection group 3 shows that the system up to now does not focus on the recovery of raw materials: very different products with regard to their structure and material composition are collected together (e.g. calculators with complex products such as mobile phones or tablet computers). From an economic point of view, this mixture of products leads to a situation where manual sorting would be more expensive than shredding – leading to relevant losses of metals such as gold, palladium or indium. Within the scope of a study by Bolland et al. (2010) analysing the influence of pre-treatment on the recovery of precious metals, the percentage of product groups on pretreatment technologies (manual as opposed to mechanical) was determined. The results show that a majority of the products would be treated mechanically, which distributes such low metal concentrations concentrations as trace metals in other fractions and impedes material recycling. According to Chancerel (2010), mechanical pre-processing only leads to recovery rates of 24% for gold and palladium in the printed wiring boards (PWBs) of mobile phones. In contrast the 'pre-processing through manual dismantling allows the recovery of 90% of the gold and palladium' (Chancerel, 2010). Using in-depth manual dismantling in two steps, Salhofer et al. (2009) stated that as much as 97% of the gold and 99% of the palladium in PWBs can be recovered.

Against this background the main focus of this paper is to develop a methodology for an optimised composition of collection groups for WEEE from the perspective of resource conservation. Facing the shortcomings described above, the aim is to take into account the amount of resource intensity or critical raw materials per product, the amount of products put on the market, and the effort to recover these materials from specific components by dismantling.

The paper is structured as follows: Section 2 describes the conceptual background; Section 3 present the results with the main data and the product categorisation for optimal collection groups from a resource perspective; and in Section 4 these results are discussed. The final Section draws some general conclusions from this case study on indium and suggests paths for further research.

2. Materials and Methods

2.1 Planning criteria for the design of collection groups

The optimal planning of collection groups and their composition requires a series of methodological steps. In the beginning, the relevant critical metals were chosen and, based on their field of application, a selection of products and relevant components were identified. These steps are described in detail in Wilts and von Gries (2012), where ten metals and 30 different small electronic devices are analysed. Based on an extensive literature review and one's own analysis, a product-component-metal matrix has been developed that shows metal concentrations and location in specific components.

The following analysis is conducted using the example of indium and is justified by the enormous future relevance of this metal in electrical and electronic products as stated in various studies (Angerer et al., 2009; Oakdene Hollins, 2011). Covering the main uses of indium in electrical and electronic products, 11 products were identified. The modular design of the products enabled this systematic approach, which starts from the metal, by way of the respective components, up to the final product

For the next step a methodological approach developed by Oguchi et al. (2011) was adopted. In the work of Oguchi et al. (2011), the statistical method of cluster analysis was used to group electrical and electronic products according to product-specific attributes. With the agglomerative hierarchical cluster analysis (Bortz and Schuster, 2010), the products can merge successively based on selected parameters. In Oguchi et al. (2011), metal concentrations and their waste generation are considered, which leads to a two-dimensional visualisation, which in turn allows the derivation of clusters of products for a collection process that aims to prioritise resource intensity.

Although this methodology is already a fundamental improvement for an optimised recycling chain, it shows a major weakness in its practical implementation. The metal concentration refers to the whole product and does not take into account the fact that critical resources are not allocated homogeneously in products but can be found in very concentrated form in specific components. In order to recover these metals, the complex structure of the product requires their dismantling and, by doing so, these inhomogeneous products are broken down into recyclable parts. Otherwise such products could not be disposed of in an economic or environmental way by following a common course of treatment. Therefore, the economic viability of recovering these resources is mainly determined by the effort needed to dismantle these specific components. Accordingly the necessary dismantling effort is decisive for the design of the collection groups, because high metal concentrations alone are useless when the dismantling of the respective component is disproportionately costly.

Therefore, in the present work, the approach of Oguchi et al. (2011) is expanded in order to include the attribute 'dismantling-ability' to realise target-oriented planning of the collection structures.

In the following analysis, the dismantling effort of products is understood as the duration of the dismantling process and the resulting costs (equipment, etc.). In this analysis, the required time for manual separation of target components (liquid crystal displays (LCDs), copper–indium–(gallium)–sulfur–selenium (CI(G)S) solar cells, white light-emitting diodes (LEDs)) was assessed as variable size, and the costs, such as tooling, were assumed to be comparable. Using this procedure a comparison of the dismantling-ability of the products could be achieved.

Because of product-related considerations, the dismantlingability resulted from products that contained more than one target component as the average dismantling effort of the relevant components.

The duration of dismantling processes is dependent on various factors, such as product-specific factors (e.g. manufacturer, product types) and process-related influences (e.g. concentration of staff) (Ohlendorf, 2006). Identifiable factors such as technical equipment can be included in the analysis, but in large part these factors constitute unavoidable fluctuations leading to variations in dismantling times. Therefore, dismantling times are to be understood as an orientation value, around which the factual times range.

Within the scope of the analysis of the dismantling-ability, dismantling times and qualitative statements were consulted. In order to gain a reliable data base, an extensive literature search and expert interviews were carried out. As a result, the dismantling-ability of the selected products is assessed as a ranked order.

2.2 Categorization of products

In order to design the collection system in groups by using cluster analysis, the grouping objects are the selected products and the similarity structures are measured by the following attributes, which are characteristic of resource-protection-oriented planning

- product-specific indium content
- product sales
- dismantling-ability.

For the calculation of the groups of products, the agglomerative hierarchical cluster analysis is applied. In this method, at the beginning the number of objects corresponding to the clusters and the clusters are combined successively (Bortz and Schuster, 2010). In this context, the advantage of this method is that the number of clusters is not predetermined and therefore, with each iteration, the effect of the decreasing number of clusters can be examined. Ultimately the optimum number of clusters can be selected.

The gradual merging of two clusters is reached through the calculation of the average distances (quantitatively measured similarity between the attributes) of each cluster and the two clusters with the smallest average distance (i.e. the greatest similarity) are added together to form a cluster (Bortz and Schuster, 2010).

To implement the cluster analysis, the planning attributes need to be brought to a common scale of measurement in order to allocate the data with each other. While the values for the product-specific indium content and quantities of product sales only needed to be aggregated to one level, the qualitative assessment of the dismantling-ability (rank order) was yet to be transformed into a quantitative assessment.

The results of the dismantling-ability of products presented as rank order did not allow an accurate determination regarding to what extent a product is easier or more difficult to dismantle. For this reason a linearity assumption was made (rating in accordance with the number of hierarchy levels).

Based on this assessment, the remaining two attributes were also brought to the same scale level 1 to 6. The assignment of these numbers to the attributes occurred by means of linear interpolation, so that the relation between them was accurately reproduced and simultaneously calculation operations between the attributes were possible. Here the highest concentrations of indium, highest product sales and the highest dismantlingability were considered as positive and were measured at 6, whereas the lowest values for these characteristics were assigned with 1. The intermediate values were finally interpolated.

Overall, this review is only valid in the context of this clustering. For instance, the indium content rated as 1 does not correspond to an exact indium concentration but instead to the lowest of the observed values.

3. Results

3.1 Product-specific and market-based Quantification

Table 1 shows the identified components and products for indium. Based on these results the respective average contents of indium and product sales were determined.

Table 1: Exemplary identification and quantification for indium in 2010 for Germany

Product	**Components**	**Average Indium Content per Component**	**Average Indium Content per Product**	**Product Sales 2010 in Germany**
		mg Indium per component	*mg Indium per kg product*	*Mg*
LCD TV (LED)	LC-Display	254	30.0	6605
	White LEDs (total)	4.4		
LCD TV (CCFL)	LC-Display	254	29.5	64414
LCD Monitor (LED)	LC-Display	79	16.4	1134
	White LEDs (total)	2.9		
LCD Monitor (CCFL)	LC-Display	79	15.8	16044
Laptop (LED)	LC-Display	39	14.4	19519
	White LEDs (total)	1.5		
Laptop (CCFL)	LC-Display	39	13.9	459
Mobile Phone	LC-Display	6	30.5	2882
	White LEDs (total)			
Digital Still Camera	LC-Display	3	21.0	1187
	White LEDs (total)			
Navigation System	LC-Display	30	100.0	1042
	White LEDs (total)			
LED Lamp	White LEDs (total)	2	8.4	1283
CI(G)S-Photovoltaic Module	Solar Cell	9045	838.5	15497

Source: compiled by the authors according to data from Behrendt et al., 2010; Bio Intelligence Service, 2011; Buchert et al., 2012; Chancerel, 2010; Displaysearch cited on The free library, 2010; European Photovoltaic Industry Association (EPIA), 2012; Gesellschaft für Unterhaltungs- und Kommunikationselektronik, 2010; Hartl, 2012; Hendrickson et al., 2010; MoE and METI, 2010; Oguchi et al., 2008; Stiftung Elektro-Altgeräteregister, 2012.

These data are intended as a snapshot of the year 2010, because the indium concentrations are of rapidly varying sizes and changing material compositions are common due to the short innovation cycles. Also, research according to market sales shows the same dynamic characteristics as the product-specific concentrations of indium. For instance, the equipment sales of LED lamps in 2012 have grown rapidly, and, coupled with indium concentrations and the market sales of 2012 compared to 2010, this has caused increased indium amounts put on the market by several kilogrammes.

3.2 Dismantling-ability of product selection

The literature searches for dismantling times indeed offered an incomplete picture; however, it did allow an initial classification of the products. Salhofer et al. (2012) specified a dismantling time of 18 min for LCD monitors. By contrast, Cryan et al. (2010) state a dismantling time of 9 min for LCD monitors and laptops. In this study, however, only the time for the dismantling of the laptop monitor was considered and not the breakdown time for the whole product. For this reason, the laptop dismantling time must be above 9 min.

Both data sources show clear added effort in the LCD TV dismantling in comparison to the dismantling of laptops and LCD monitors.

Böni and Widmer (2011) state a dismantling time of 15 min for all three products. It is an average value for these products, and for that reason the value is only used to obtain a ratio of thedismantling time to the remaining products.

An example of the dismantling of a mobile phone showed that housing, accumulator and keypad can be removed manually without tools within seconds (Greif, 2007). At 90 s, the release of six bolts, which is required for the subsequent removal of the printed circuit board and the LCD, is the most time-consuming aspect (Greif, 2007). The total duration of the process is about 2 min (Greif, 2007). Table 2 summarises the results of the literature search.

Table 2: Dismantling time of product selection for manual dismantling to the target-component

<table>
<tr><th colspan="11">Time for dismantling the target-component[1], in <i>Minutes</i>
Target-Component: LC-Display, White LEDs, Solar Cell</th></tr>
<tr><th>LCD TV (LED)</th><th>LCD TV (CCFL)</th><th>LCD Monitor (LED)</th><th>LCD Monitor (CCFL)</th><th>Laptop (LED)</th><th>Laptop (CCFL)</th><th>Mobile Phone</th><th>Digital Still Camera</th><th>Navigation System</th><th>LED Lamp</th><th>CI(G)S-Photovoltaic Module</th></tr>
<tr><td>▨</td><td>12[a]</td><td>▨</td><td>9[a]</td><td rowspan="3">▨</td><td>9[a]</td><td rowspan="3">2[d]</td><td colspan="4" rowspan="3">▨</td></tr>
<tr><td colspan="2">24[c]</td><td colspan="2">18[c]</td><td rowspan="2">15[b]</td></tr>
<tr><td>▨</td><td>15[b]</td><td>▨</td><td>15[b]</td></tr>
</table>

Source	**Note**
a: Cryan at al., 2010	Dismantling time refers only to the dismantling of the monitor of the Laptop; the remaining part was separated previously from the Laptop.

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[1] Numbers are valid for a gradual, non-destructive and complete dismantling process. The times are indicative of the dismantling of the target-component because the LC-display and the backlight are in high dismantling depth.

b: Böni and Widmer, 2011	It is a mixed value from the respective dismantling time of LCD TV (CCFL), LCD Monitor (CCFL) and Laptop (CCFL).
c: Salhofer et al., 2012	Between the types of backlight (LED/CCFL) is not explicitly distinguished.
d: Greif, 2007	Example dismantling of the Nokia 6100, Target-component: LC-Display.

Source: compiled by the authors according to data in the table itself

For further consideration of these data and in order to gain more information about the remaining products, relevant experts were interviewed. According to M. Bergamos (by email interview conducted by the author on the manual dismantling effort of selected products, Mörfelden-Walldorf, in 2012), CI(G)S-photovoltaic modules and LED lamps are very complicated to dismantle compared to other products. The dismantling of solar modules is determined by solving their complex encapsulation. With respect to LED lamps, the solder connection in between every single LED and the LED printed circuit boards collectively add up to a huge effort in the breakdown process.

In contrast, the duration of the dismantling process of mobile phones is similar to digital cameras and navigation systems and the quickest when compared to the remaining selected products according to N. Mann (in an interview conducted by the author on dismantling practice at the Recyclingcenter in Frankfurt on the Main, in 2012).

The dismantling effort required for backlights as a whole in LCD TVs, LCD monitors and laptops is in principle quicker if the products are equipped with cold cathode fluorescent lamps (CCFL) as backlights rather than with LED backlights (according to M. Bergamos). LED backlights are generally very extensively plugged in to products – mostly through the use of adhesive bonding. In contrast, products with CCFL used for backlighting are designed in a modular and interchangeable way.

Moreover, it is conceivable that without unbolting through a well-directed breakup (since there is no potential danger of a possible damage to the lighting) such products with LED backlights could be dismantled faster in terms of the LCD separation (see assessment in brackets in table 3) according to U. Brettschneider (in an interview conducted by the author on dismantling practice at the Azur company in Mühltal, in 2012). But since the type of backlight can only be identified after the non-destructive and gradual dismantling process, this dismantling practice is not yet possible, according to U. Brettschneider. Certainly this issue could be an interesting one for the future, if there are no more CCFL backlit products in the waste stream or manufacturers indicate the type of backlight used in their products

Obviously, the dismantling effort of the single LEDs out of the LED backlight increases in proportion to the number of LEDs. Therefore a search for mean numbers of LEDs in products provides a further indication of the different dismantling-ability. Because of the product-related consideration, dismantling-ability of display products is the result of the average dismantling effort of the relevant components (LCDs, LEDs).

Table 3 summarises the results of the author interviews with U. Brettschneider, N. Mann and M. Bergamos, as described above. The evaluation of the dismantling times occurred in three categories: x, xx, xxx. These crosses represent the dismantling effort, which increases with the number of crosses.

Table 3: Qualitative assessment of dismantling time of product selection for manual dismantling to the target-component

	Qualitative Assessment of Dismantling Time[2], *x: low to xxx: high* Target-Component: LC-Display, White LEDs, Solar Cell										
	LCD TV (LED)	LCD TV (CCFL)	LCD Monitor (LED)	LCD Monitor (CCFL)	Laptop (LED)	Laptop (CCFL)	Mobile Phone	Digital Still Camera	Navigation System	LED Lamp	CI(G)S-Photovoltaic Module
Separation of the **LC-Display / CCFL-backlight**	xx^{fe} x^{g}						x^{gfe}			▨	▨
Separation of the **LED-backlight** / Printed Circuit Boards **as a whole**	xx^{feg} $(x)^{e}$						xx^{g} x^{fe}			xx^{g}	▨
Separation of the white **LEDs** from the LED-Printed Circuit Boards	xxx^{g}	▨	xxx^{g}	▨	xxx^{g}	▨	xxx^{g}			xxx^{g}	▨
Separation of the **Solar Cell**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	xxx^{g}

Source	**Note**
e: Brettschneider, 2012	There were no dismantling times made, but measuring of the differences in the dismantling times in ranks. The bracketed values are valid if it is already known before the dismantling process what kind of backlight is installed.
f: Mann, 2012	Gave no times, but measured the differences in the dismantling times in ranks.
g: Bergamos, 2012	

Source: compiled by the authors according to data in the table itself

Based upon this research of dismantling times and qualitative statements, the products are ordered hierarchically in terms of their dismantling-ability. The results for mobile phones, digital still cameras, navigation systems, CI(G)S photovoltaic modules as well as LED lamps can clearly be attributed to consideration of the results from Tables 2 and 3. The remaining ranking results are arrived at mainly from the combination of the facts that CCFL-backlit devices have better dismantling-ability and that LCD TV (CCFL/LED) are worse to dismantle than the respective laptops and monitors as shown in Table 2; they are also determined by the number of LEDs (TVs have generally much more LEDs than laptops and monitors). Table 4 shows the results, whereby the dismantling effort rises in the ranking from top to bottom.

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[2] Numbers are valid for gradual and non-destructive dismantling process of target components, except for the numbers in brackets.

Table 4: Dismantling-ability of the product selection

Product Selection Sorted by Dismantling-ability
Mobil Phone, Digital Still Camera, Navigation System
Laptop (CCFL), LCD Monitor (CCFL)
LCD TV (CCFL)
Laptop (LED), LCD Monitor (LED)
LCD TV (LED)
CI(G)S-Photovoltaic Module, LED-Lamp

Source: compiled by the authors

3.3. Categorization of products by indium concentration, product sales and dismantling-ability

The accomplishment of the hierarchical cluster analysis provided 12 possible results, which differed according to their cluster number (from two up to 11 clusters) and the resulting cluster size. The final number of clusters was determined based on the fact that, with the increasing number of clusters, the heterogeneity of the products decreases, whereas the logistics effort, such as sorting or storing the products, increases. To resolve the conflicting objectives of maximising the similarity within clusters and minimising the number of clusters for a viable starting point of product sorting, the number of clusters was determined using statistical criteria and qualitative considerations.

In the context of the statistical analysis, quantifying the increasing dissimilarity of the products within a cluster is achieved by a decreasing number of clusters, using the variance (Fett, 2008). Given this heterogeneity measurement, particularly large differences between the heterogeneity measurement of a clustering and the subsequent clustering, point to a relatively large increase of dissimilarity, so that the choice of the number of clusters before such differences is favourable (Fett, 2008). Against this background a cluster of four numbers is advantageous. In conjunction with a qualitative assessment in the general context (e.g. current number of collection groups), these results lead to a final determination of five clusters with the products shown in Table 5.

Table 5: Results of the cluster analysis

Cluster Number	Categorization of Products
5	LCD TV (LED), LCD Monitor (LED), Laptop (LED)
	LCD TV (CCFL)
	Mobile Phone, Digital Still Camera, Navigation System, Laptop (CCFL), LCD Monitor (CCFL)
	LED-Lamp
	CI(G)S-Photovoltaic Module

Source: compiled by the authors

4 Discussion

To discuss the cluster results, the average concentrations of indium, the product sales and the average dismantling-ability of each cluster were calculated to compare the clusters in terms of their attributes. Additionally, the indium amounts put on the market, as absolute amounts of the clusters, were calculated.

Table 6: Quantification of attribute values of each cluster in 2010 for Germany

Cluster	**Products**	**Average Dismantling-ability per Cluster** *1: low, 6: high*	**Average Indium Content per Cluster** *mg per kg*	**Product Sales per Cluster** 2010 *Mg*	**Put on the Market Indium Amounts per Cluster** 2010 *kg*
1	LCD TV (LED), LCD Monitor (LED), Laptop (LED)	2.8	18.3	27258	499
2	**LCD TV (CCFL)**	**4**	**29.5**	**64414**	**1900**
3	Mobile Phone, Digital Still Camera, Navigation System, Laptop (CCFL), LCD Monitor (CCFL)	5.2	22.1	21614	478
4	LED-Lamp	1	8.4	1283	11
5	CI(G)S-Photovoltaic Module	1	838.5	15497	12994
Median		2.8	22.1	21614	499

Source: compiled by the authors

In order to evaluate the results, as a threshold, the median of each attribute was used (see Table 6). The results show that cluster 2 (highlighted in bold) is the only one consistently above the threshold. Collection group 2 has a relatively high dismantling-ability coupled with high product sales and high indium concentrations; so for gaining high indium recovery rates, an appropriate recycling focus on this group is targeted.

For the remaining clusters, the attributes are contrary to each other. For example, CI(G)S-photovoltaic modules indeed show a huge potential of indium amounts, but they have a strikingly low dismantling-ability.

Figure 1 clearly shows the influence of the different values of attributes of the products on the formed clusters.

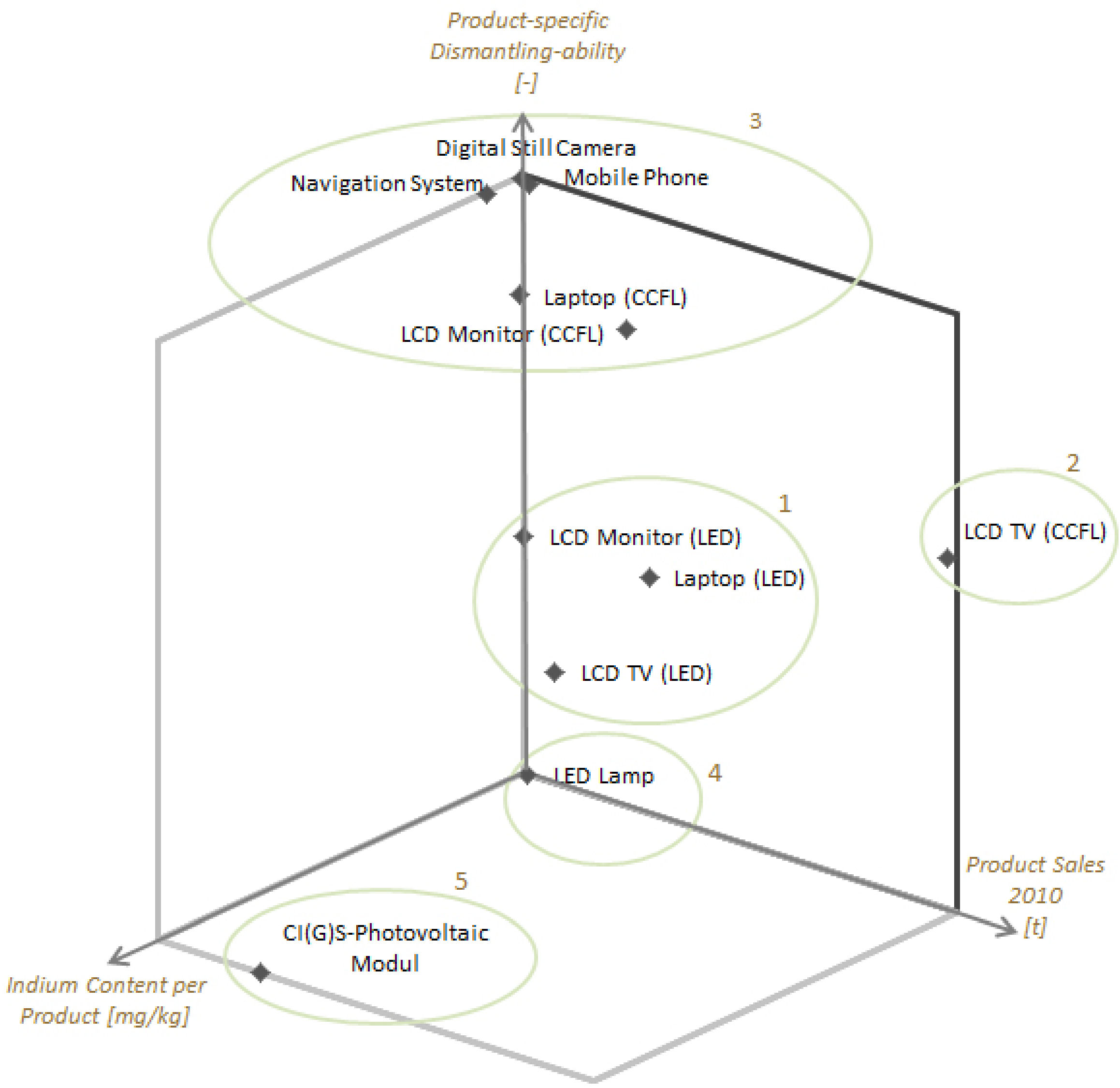

Figure 1: Categorization
Source: compiled by the authors

The figure illustrates the extent of the characteristic properties of the clusters and thus opens up a range of options, which allows optimisation of the treatment and recycling of the products. Apart from the identification of the cluster, which achieves suitable results in all attributes and therefore makes the recovery of indium highly resource efficient, the other clusters can also be led towards an adequate treatment.

For example, when clusters contain products that are easily dismantled and show high product-specific indium contents with low product sales, the storage of such products could be considered. The products could be stored until a sufficient amount has been collected, so as to be able to perform the recovery in a more profitable manner. In particular, because of the high dismantling-ability of such collection groups, the components can be concentrated by accumulation. Such considerations are especially useful for products where a significant increase in market demand is expected.

In collection groups that have a poor dismantling-ability and high concentrations of indium, recovery is initially not economically feasible. But at this point the future relevance of the products plays an important role: a further increase of these quantities may initiate technological developments that allow profitable indium recovery. Especially in the case of CI(G)S photovoltaic modules, considerations such as storage due to their enormous indium concentrations play a central role.

For collection groups that neither show high potential of indium amounts (with respect to the product-specific concentration and amounts put on the market), nor are particularly easy to dismantle, the recovery can be performed by focusing on bulk metals. The same applies to clusters in which storage or something close to it does not come under consideration owing to the absence of any future relevance. In this case, recycling structures, such as shredders, will be used in a resource-protection-oriented way.

Accordingly, if good results are not achieved in all attributes, this does not mean that the resources are not recovered. Dismantling-ability is not always obligatory for recovery, but in all cases it provides a better starting position. Thus the grouping serves as a means of initiating the planning of subsequent disposal paths; this of course depends on aspects such as the recovery techniques and has to be decided depending on the current situation (recovery options, metal prices, etc.).

Overall, by using such design of collection groups, not only can the recycling of critical metals be achieved but also improved recycling of all resources. Depending on the attribute values of the clusters, resource-based planning of the disposal procedure can take place, which could methodically be extended to all critical metals, as well as to all electrical and electronic equipment.

5. Conclusions

In the present work, a method has been developed that permits the optimisation of collection groups from the perspective of resource conservation. The resulting analysis has shown that the methodology aims not only to gain clusters that achieve good results in all attributes but also enables transparent planning. Aspects such as technical developments in indium recovery can be adequately taken into account with the grouping of products with similar attributes, because dismantling-ability and indium concentrations are important parameters for indium recovery. Waste management planning for a collection group with completely different attributes in this respect cannot adequately take into account such considerations as recovery options or price developments (directly linked to indium amount). For new products with highly intense bonding between the materials (e.g. tablets), which are quite hard to dismantle, economically feasible recovery options have to be developed (which do not require a dismantling), and so the cluster analysis enables these products to be accumulated for further operations.

Overall, the results highlight that beyond an increased collection rate – as foreseen in the revised WEEE directive (directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (EC, 2012) – a more systemic approach will be needed to close the loop for critical metals.

A resource-oriented design of collection groups – comprising 'design for dismantling-ability' and a pure knowledge of component contents – depends on a high level of information as well as, to a high degree, an improved information exchange between producers and recyclers. Article 15 of the WEEE directive already sets the framework for such knowledge management: "In order to facilitate the preparation for re-use and the correct and environmentally sound treatment of WEEE, including maintenance, upgrade, refurbishment and recycling, Member States shall take the necessary measures to ensure that producers provide information free of charge about preparation for re-use and treatment in respect of each type of new EEE placed for the first time on the Union market within one year after the equipment is placed on the market." (EC, 2012). Nevertheless WEEE experts confirm that this cooperation works very inefficiently regarding the recycling of critical metals for several reasons:

- Often the product- or component-producers themselves have insufficient information on content and location of specific critical metals due to complex supply chains. The original equipment manufacturers focus on functionality and legal requirements such as REACH (EC, 2006) and ROHS (EC, 2011) when ordering their components – as do the producers of components when ordering specific parts (Lauridsen and Jørgensen, 2010). In this global network the material composition of specific products can also change on a daily basis, depending on changes in raw material prices.
- Producers are often not aware of the type and structure of information that the recyclers on different levels (dismantling, pre-processing etc.) need in order to be able to localise the critical metals in a discarded product or component. Often they also keep this kind of information confidential because competitors could derive insights into technical innovations based on the material composition.

In contrast, information on market sales is, at least in Germany, carefully documented. The presented design of collection groups based on market sales and not on current waste generation promises planning based on foresight. In order to implement the approach developed in this paper, the involvement of a calculation model considering the length of the product use phase could integrate the point in time at which the products become WEEE. Such a modification should be oriented around lifetime distribution, which considers that purchased products in a given year will not become waste in the same year. A study by the Nordic Council has dealt with the determination of lifetime distributions for WEEE (Nordic Council, 2009) and can provide such data.

Besides the aforementioned lack of information and the enhancement options regarding the planning criteria for collection groups, the method has to be expanded beyond indium in order to implement the developed approach. Indium is an important indication in terms of criticality resource intensity, but of course a metal-specific indicator alone will not be sufficient to develop collection systems. From a resource perspective, such an indicator has to take into account the huge differences in the 'ecological rucksacks' of raw materials, the amount of energy, biotic materials and so on, to produce a tonne of metal such as copper or gold. The 'total material requirement' (TMR) would be a kind of best-case indicator because it includes all the resource requirements along the value chain, including whether the raw material is generated abroad, and gives a clear figure for all materials contained in the different products.

Such an indicator would also help to switch WEEE regulation from the recent weight-based system for collection and recyclingrates to a more resource-efficiency-based system that would set much higher incentives for recovering critical materials, instead of focusing mainly on base metals or plastics (Wilts, 2013).

Apparently a successful implementation of the rearrangement of collection groups requires far-reaching measures, such as the restructuring itself. In the overall context, however, such single measures imply whole system changes, which, in the face of the current deficiencies in recycling and the complex requirements to secure the supply of raw materials, are much needed.

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