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Feasibility study for setting-up reference values to support the calculation of recyclability / recoverability rates of electr(on)ic products – DRAFT REPORT

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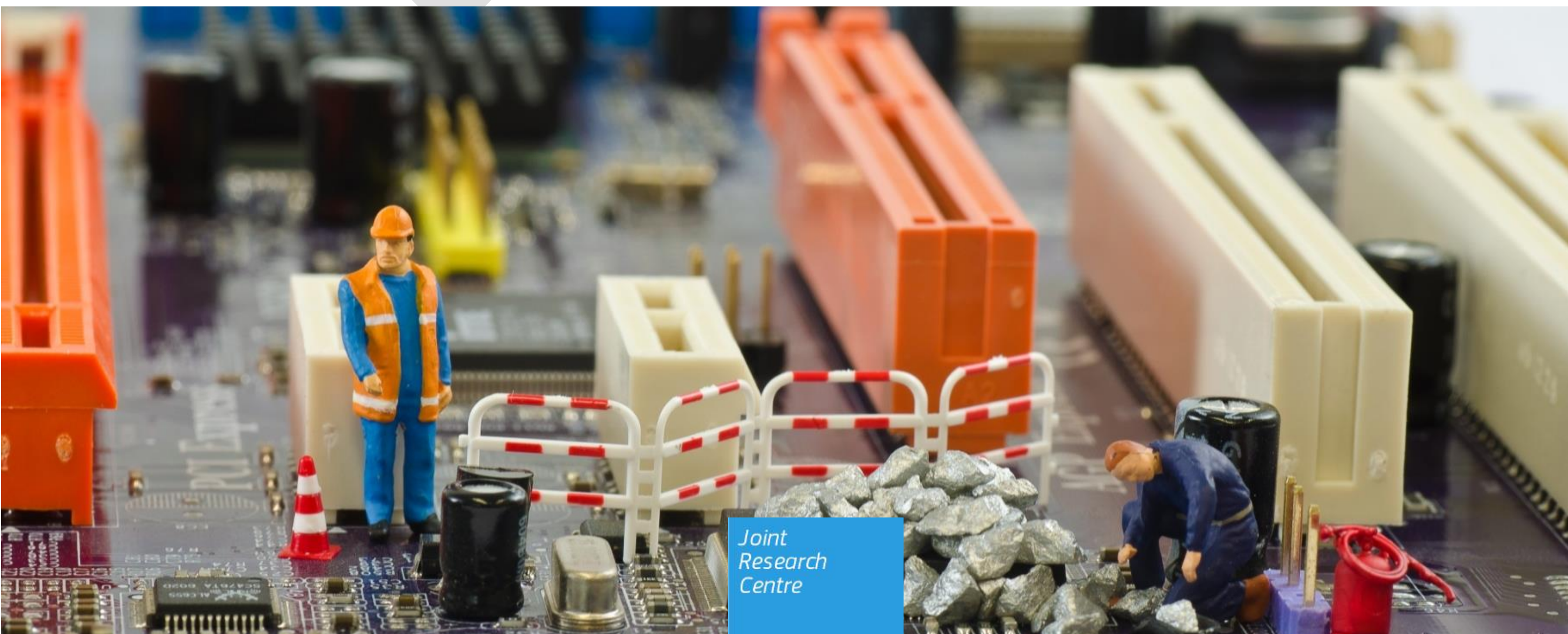

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Feasibility study for setting-up reference values to support the calculation of recyclability / recoverability rates of electr(on)ic products – DRAFT REPORT

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Abstract

The ‘feasibility study for setting-up reference values to support the calculation of recyclability / recoverability rates of electr(on)ic products’ commissioned by the Joint Research Centre is embedded in the activities of the European Commission targeting the improvement of the resource efficiency by promoting the recyclability of products. The objectives of the study are to define key harmonized methodological aspects to calculate reference values on recycling and recovery rates of materials and components for electr(on)ic products, and to assess the benefits and limitations associated to the development and maintenance of such reference values. It fits well into the European Commission’s Circular Economy Action Plan of 2015 that calls for more systematic analysis of recyclability under Ecodesign.

To quantify the recycling and recovery rates of materials and components, three main options are possible and combinable: (1) use data on RRR compiled to comply with the reporting requirements of the WEEE directive for WEEE input flows and combined with analyses of the input composition, (2) conduct, e.g. in the frame of research projects or certification processes, additional batch analyses at treatment operators, and (3) model the processes with simulation tools. In this study, the focus was set on option 1. The frame set by the definitions, methods and rules adopted in the European Waste Framework Directive and in the WEEELABEX standard served as a methodological basis to define the requirements on the data. The data collected through batch analyses in WEEE treatment facilities, compiled using the software WF-RepTool, checked and validated, were linked with data on the WEEE input flow to calculate material-specific recycling and recovery rates. To calculate recyclability and recoverability rates of products, the material-specific rates are combined with the bill of materials of the product. One task aimed at testing the data collection methodology on few materials (including some Critical Raw Materials) and components contained in two case studies chosen for their relevance for ecodesign requirements: washing machines and laptops.

The calculation of reference values using a harmonized scope and harmonized methods would provide common data reflecting the economically running treatment processes used by WEEE treatment operators for calculating recyclability and recoverability rates of products. The calculated recyclability and recoverability rates of products can be used as one of the indicators of the material efficiency of a product, and integrated into further environmental assessments. The proposed method for the production of the reference values relies on the cooperation with stakeholders, for instance operators of treatment facilities and WEEE compliance schemes. The method provides new opportunities to link product design and recycling, as well as to enhance the dialogue between the stakeholders.

Executive summary

Context

The ‘feasibility study for setting-up reference values to support the calculation of recyclability / recoverability rates of electr(on)ic products’ commissioned by the Joint Research Centre is embedded in the activities of the European Commission targeting the improvement of the resource efficiency by promoting the recyclability of products. In the EU action plan for the Circular Economy, the European Commission announces to “promote the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive” and to simplify and harmonise definitions and calculation methods for recycling and recovery rates (RRR). Moreover, a standardization mandate was issued in December 2015 by the European Commission as a first action of the Plan that asks to deal with “recyclability/recoverability indexes or criteria, preferably taking into account the likely evolution of recycling methods and techniques over time” and possibly associated “reference tables”. This report should be seen as an input to this standardization process that is starting. The development of reference values on recycling and recovery rates (RRR) using a harmonized scope of the calculation and harmonized methods would provide common data reflecting the economically running treatment processes currently used by WEEE treatment operators. The reference values should be applicable to conduct assessments of the environmental performance of products using methods, standards and indicators that consider mass-based recyclability and recoverability rates, like the technical report IEC/TR 62635, the Resource Efficiency Assessment of Product (REAPro) method, the Product Environmental Footprint method and the Methodology for Ecodesign of Energy-related Products (MEErP). References values could also be used by manufacturers to perform their own assessment to support design activities.

Objectives

The objectives of the study are to define key harmonized methodological aspects to calculate reference values to support the calculation of recyclability and recoverability rates of electr(on)ic products, to evaluate the activities needed to collect data and to maintain the database on a timely manner, as well as to assess the benefits and limitations associated to the development of such a database.

The study was composed of four main tasks. In task 1, the principles and main methodological aspects to calculate the reference values, i.e. material-specific recycling and recovery rates, were defined. Task 2 aimed at testing the data collection methodology on few materials and components. Drawing conclusions and making recommendations for the Joint Research Centre were the objectives of task 3. Experts supported the progress of the study for instance by proposing options for the development of the methodology, sharing knowledge and contacts and commenting the reports to improve them.

Preliminary assumptions and methods

To quantify the recycling and recovery rates of materials and components, three main options are possible and combinable: (1) use data on RRR compiled to comply with the reporting requirements of the WEEE directive for WEEE input flows and combined with analyses of the input composition, (2) conduct, e.g. in the frame of research projects or certification processes, additional batch analyses at treatment operators, and (3) model the treatment processes with simulation tools. In this study, the focus was set on option 1. The frame set by the definitions, methods and rules adopted in the European Waste Framework Directive and in the WEEELABEX standard served as a methodological basis to define the requirements on the data. The data collected through batch analyses in WEEE treatment facilities, compiled using the software WF-

RepTool, checked and validated, was linked with data on the WEEE input flow to calculate material-specific recycling and recovery rates. To calculate recyclability and recoverability rates of products, the material-specific rates are combined with the bill of materials of the product.

The key assumptions of the developed method to calculate the material-specific RRR were:

- The material-specific recycling and recovery rates are calculated for mixes of products treated together in the WEEE collection and treatment flows. The rates are assumed to be valid for all materials contained in the WEEE flow, irrespective of the type of product in which it was embedded. This reflects the reality in WEEE treatment facilities, but the influence of the non material-related design features of an individual product on its recyclability and recoverability (rates) can hardly be derived from the collected data.
- The calculation of the material-specific recycling and recovery rates is based on the whole process chain including all interim and final treatment technologies. It does not consider separately each treatment step. In the collected reference values, the reports roughly describe the end-of-life scenario but do not detail the treatment technologies used. This reduces the efforts for data collection and the confidentiality issues, but reduces also the possibility of plausibility control and the transparency.
- The recycling and recovery rates are intended to be retrieved from operators using economically running best available techniques.
- The material-specific recycling and recovery rates are calculated by dividing the mass of the share of the final fractions produced by the treatment chain and classified as recycled or recovered by the mass of the corresponding material contained in the WEEE input flow. The mass of the share of the final fractions classified as recycled or recovered is determined by batch analyses at the operator. The composition of WEEE input flow is an average measured in campaigns and does not exactly corresponds to the composition of the analysed batch. The discrepancy between composition of the analysed batch and composition data taken into account to calculate the rates creates uncertainties on the calculated material-specific recycling and recovery rates.

Results

The developed methodology was tested on two case studies chosen for their relevance for ecodesign requirements: washing machines and laptops.. For these two product groups, data on the average material composition were compiled into a bill of materials and generic end-of-life scenarios were developed. The WEEE compliance scheme Eco-systèmes selected from their operators treating the WEEE flows 'flat panel display appliances' (for laptops) and 'large household appliances' (for washing machines) the three first step operators achieving the highest RRR with their downstream acceptors. Their batch report data were analyzed to determine the mass of the final fractions produced for the years 2013 and 2014. The mass of the share of the final fractions achieved by treatment and which use is classified as recycled or recovered was divided by the mass of the corresponding material in the input of the WEEE flow. This method was applied to calculate the RRR of nine materials contained in laptops and seven materials contained in washing machines, with a special attention set on the composition of the printed circuit boards (PCBs). For each material, the average recycling and recovery rate (RRR), the standard deviation of the three operator-specific RRR, the minimum and the maximum RRR were calculated. Furthermore, the metal-specific recycling rates of cobalt from batteries, palladium from populated PCB and indium from flat panel display appliances were investigated.

The activities necessary for setting-up the reference values and maintaining the database were analysed. The setting-up includes the programming of the database, the collection of representative bills of materials, the identification of stakeholders willing, allowed and able to provide data, the selection of operators including downstream acceptors to be considered, the definition of the end-of-life scenarios, the analyses of treatment batches and input WEEE flows, the data compilation and the assessment of the validity of the reference values. Also activities to collect additional data on the input composition of the batches and for a better differentiation of the materials were analysed.

Next steps

The main recommendations to support the calculation of the reference values relate to the improvement of the available data. On the one hand, activities are needed to collect more detailed data for some of the materials. This concerns especially plastics (differentiation of the resins), complex parts and batteries. On the other hand, the harmonization of the methods and assumptions used to calculate recycling and recovery rates across the member states of the European Union is a key to make more harmonised data existent. Shaping incentives to participate and dealing with confidentiality is very relevant for the calculation of the RRR, which relies on the willingness of the stakeholders (WEEE compliance schemes and operators) to provide data. In several aspects, the methodology needs to be refined. For example, although a proposal was made to decide over the number of operators to be selected and the criteria to be used for the selection, there is still need for further research on these aspects. This concerns also the methods used to define one or more end-of-life scenarios for the WEEE input flows, to deal with new materials that are not found yet in the treated WEEE, to ensure and improve the data validity and representativeness, to quantify the uncertainty and the variability and to reflect it into the reference values. Further research is also needed to better understand the influence of design decisions and chosen treatment processes on recyclability and recoverability rates of products.

Expected benefits

The main benefit of the database to be developed is the provision of harmonised and reliable reference values on the recycling and recovery rates for different materials currently achieved by the operators treating WEEE. It sets a clear frame in terms of scope and method for the calculation of mass-based recyclability and recoverability rates of products. In principle, the method proposed to set up reference values could be extended to the other product groups for which European legislations require the calculation of recycling rates, i.e. vehicles, batteries and packaging materials.

The proposed method for the calculation of the reference values provides new opportunities to link product design and recycling, as well as to enhance the dialogue and cooperation between the stakeholders. The database could hence be a good tool to support such cooperation, which was recently re-emphasised in the context of article 15 of the WEEE Directive. The method relies on the cooperation with stakeholders, for instance operators of treatment facilities, WEEE compliance schemes and experts involved in the efforts towards harmonisation of the calculation of recycling and recovery rates. The developed methodology needs to be embedded in the current discussion on the relevance and the ability to implement recyclability and recoverability indicators for future product policy development towards more material efficiency, including industry driven activities in that direction.

1 Introduction

The introduction presents the background that led to the feasibility study, the objectives of the study, the state-of-the-art regarding methods and data available to calculate recyclability and recoverability rates of products, and the structure of this report.

1.1 Background

Already in 2003, the European Commission published the Communication COM/2003/0572 'Towards a Thematic Strategy on the Sustainable Use of Natural Resources', aiming "to launch a debate on a framework for using resources" [1]. Since this time, many policy activities aiming at enhancing the resource efficiency were launched and put into practice, including the Flagship initiative of the Europe 2020 Strategy, the European Resource Efficiency Platform and the Raw Material Initiative.

Resource efficiency is not just concerned with the amount of resources consumed, but the use of natural resources in relation to their utility and the resulting environmental impact [2]. The need to assess and improve the performance of products regarding resource efficiency was formulated in particular in the Roadmap to a Resource Efficient Europe [3], which recommends including more resource relevant criteria in the assessment of the environmental performance of products. In the recent EU action plan for the Circular Economy [4], the European Commission announces to "promote the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive" (section 1.1) and to simplify and harmonise definitions and calculation methods for recycling and recovery rates (RRR) (section 3). At the Joint Research Centre, the REAPro method was developed to assess the product performance according to six sets of resource efficiency and waste management criteria [5]:

- "Re-usability/recyclability/recoverability rates" (per mass) of a product
- "Environmentally based re-usability/recyclability/recoverability rates" (per unit of environmental impact)
- "Recycled content rate" of a product (per mass)
- "Environmentally based recycled content rate" (per unit of environmental impact)
- "Use of hazardous substances"
- "Durability"

The calculation of the "re-usability/recyclability/recoverability rates" of a product is the scope of this study.

1.2 Objectives of the study

Ardente and Mathieux [6] set the frame for this originally named 'feasibility study for setting-up a European database for recyclability/ recoverability rates of materials / components for various electr(on)ic equipment categories' by writing that "the availability of robust and representative data concerning the recycling rates of materials and parts is a key issue of the recyclability index". They "noted that further research is needed on this subject, by developing more comprehensive and representative data sets."

The study investigates the feasibility of the setting-up reference values of recycling and recovery rates (RRR) of materials and components for various product categories. It follows several goals:

- define key harmonized methodological aspects to develop such database (e.g. definition of recyclability and recoverability rates; perimeters considered in the calculation)
- evaluate the activities needed to collect data (including the involvement of key stakeholders) and to maintain the database on a timely manner
- enable the JRC to assess the benefits and limitations associated to the development of such a database.

The study was composed of four main tasks:

- Task 1: Defining the principles and main methodological aspects of the database to be developed;
- Task 2: Testing data collection methodology on few materials / components;
- Task 3: Drawing conclusions and making recommendations for the JRC;
- Task 4: Producing a final feasibility study.

1.3 State-of-the-art

1.3.1 Available methods and standards

The assessment of the performance of products regarding resource efficiency raises questions related to methodology and data availability. In Europe, progress was made from a methodological perspective through the publication of the ILCD Handbook [7], the Product Environmental Footprint method [8], the Resource Efficiency Assessment of Product - REAPro method [9] and the Material-efficiency Ecodesign Report and Module to the Methodology for the Ecodesign of Energy-related Products (MEErP) [10]. Efforts to make available data for these assessments include the European Life Cycle Database (ELCD) and the Life Cycle Data Network. Data gaps were and are a bottleneck that challenges the applicability and the actual implementation of the assessment methodologies.

One of the indicators for the resource efficiency of a product is its recyclability. An overview of approaches to define recyclability and recoverability of products was provided by Maris and Froelich [11]. The technical report IEC/TR 62635 provides a methodology "for calculating the recyclability and recoverability rates" [12], which was used as a basis to refine the JRC method [6]. The OECD Sustainable Manufacturing Toolkit recommends to calculate a recyclability indicator [13]. A further source of methodological information is the technical rule PAS 1049 "Transmission of recycling relevant product information between producers and recyclers - The recycling passport" [14]. "Design for end of life" is also one criterion of the rating system for greener electronics EPEAT (IEEE 1680 Family of Standards for Environmental Assessment of Electronic Products [15]). Section 4.3 "Design for end of life" of the EPEAT Conformity Assessment Protocol addresses [16]:

1. Ability to disassemble product
2. Recyclability of plastics
3. Materials with special handling needs
4. Planning and analysis for end of life, including the calculation of the indicator "reusable/recyclable percentage", defined as the weight of materials that is recyclable, divided by the total weight of the product, multiplied by 100

The need to calculate reference values on recycling and recovery rates based on available treatment technologies and markets is claimed by several groups, initiatives and projects, including Ardente & Mathieux [6] and the iNEMI Repair and Recyclability Metrics project [17], who wrote that the "industry needs an incorporated metric that reflects actual recovery rates of the product in the region where the product is sold".

1.3.2 Estimates on recycling and recovery rates available in the literature

Even though some standards, methods and research groups presented in this section published estimates of recycling rates, reliable data could not be found in the literature. The published estimates are mainly based on expert knowledge and information on their source, validity and representativeness is lacking. The estimates cannot ensure a good data quality and should only be used if measurements are not available and cannot be conducted.

WEEELABEX [18] publishes in session D3.2 of annex D assumptions on recycling and recovery rates (Table 1) that can be applied, if no specific data are available, for:

- components of low volume in WEEE, which are in many cases forwarded via metal traders (cables, printed circuit boards, motors) and therefore data collection is difficult or
- fractions forwarded via other producer systems responsible for collection and treatment (for example batteries) or
- data collection is difficult/seen as not necessary (capacitors)

Table 1: Simplifying assumptions on recycling and recovery rates allowed according to WEEELABEX [18] if no specific data are available

Components	**Technology**	**Estimation yield / composition**	**Estimated use**	**Standard classification**
Mixed batteries and accumulators	Battery recycling plant	50 % metals (estimate) 50 % non metals	To be completed	50 % recycling 50 % thermal disposal
Mixed cables	Specific cable shredder plant	30 % Cu 70 % plastics	Cu > Cu recovery No information – municipal waste incineration	30 % recycling 70 % thermal disposal
Capacitors	High temperature incineration	mixture	Hazardous waste incineration	100 % thermal disposal
Printed circuit boards	Copper smelter or precious metal refining	To be completed		30 % recycling 30 % energy recovery 40 % thermal disposal
Motors	To be completed			100 % recycling

The IEC/TR 62635 publishes in Annex D “Examples of treatment scenarios” recycling and recovery rates for product parts which require selective treatment, product parts with a single recyclable material, product parts difficult to process and product parts which go to separation process. The published recycling and recovery rates come from two sources:

1. The Korea Electronics Association
2. The French study Eco’DEEE - End of life Recovery conscious design of electr(on)ic equipment [19]

Also the standard CEN/TS 16524 publishes estimates of recycling rates for metals, plastics and glass.

Default re-use, recycling and recovery rates for several materials are integrated in the MEErP tool [20]. These rates, presented in Table 2, can be changed by the user. The assumptions and EoL scenarios leading to the RRR are not clearly described.

Table 2: Mass fractions of materials considered as re-used, recycled and recovered in the MEErP [20]

	Rate (from Inputs)							
	Bulk Plastics	Tec Plastics	Ferro	Non-ferro	Coating	Electro-nics	Misc. excl. refrigerant	Refrige-rant
Re-use	1%	1%	1%	1%	1%	1%	1%	1%
Recycle	29%	29%	94%	94%	94%	50%	64%	30%
Recover	15%	15%	0%	0%	0%	0%	1%	0%

1.4 Description of the sections of the report

The report is divided in 8 chapters.

The chapter following the introduction presents definitions, the objectives of the calculation of reference values, which feasibility is investigated in this study, the scope in terms of products and WEEE treatment processes, and the methods to collect data on recycling and recovery rates (RRR) for materials and components. Chapter 2 also addresses issues related to data validity and a structure for the database is proposed.

The developed methodology was tested on two case studies (laptops and washing machines). The results are presented in chapter 3. Data the end-of-life (EoL) scenarios, the bill of materials of the products and the RRR were collected and compiled with the aim of calculating the recyclability and recoverability rates of the products.

In chapter 4, the activities to build the database structure, collect bill of materials, produce the reference values and maintain the database are assessed to study the feasibility of the database.

Chapter 5 addresses key aspects that were raised in the prior chapters. The methodology testing showed that data for some materials like plastics and complex parts are missing. Methodological issues related e.g. to the use of the RRR, including the description of the EoL scenarios and the data validity are discussed and recommendations were formulated. Some possibilities to extend the database and its applications are described in chapter 6. In chapter 7, some main recommendations are summarised. Conclusions are drawn in chapter 8.

2 Methodology

Chapter 2 presents definitions, the frame of the study and the methodology that was chosen out of possible methodological options. The developed methodology is then tested in chapter 3 and discussed in chapter 5.

2.1 Definitions

The recyclability of a product is defined as the "ability of waste product to be recycled, based on actual practices", which implies the "profitable and environmentally sound process based on the current practices and market" [6]. The recyclability rate is calculated, according to the formula presented in the revised method to calculate the re-usability, recyclability and recoverability rates [6] and in the technical report IEC/TR 62635 [12], as the "ratio of recyclable product mass to total product mass" (Table 3). The definitions of terms like "recycling" and "recovery" are given by the Waste framework directive [21].

Table 3: Formula to calculate the re-usability, recyclability and recoverability rates for products [6]

Rate	Formula	Variables
re-usability	$R_{use} = \frac{\sum_{i=1}^{N} m_{reuse,i}}{m} \cdot 100 \quad [\%]$	R_{use} = Reusability rate [%] m = total product mass [kg] $m_{reuse,i}$ = mass of the ith reusable part [kg] N = number of reusable parts
recyclability	$R^{*}_{cyc} = \frac{\sum_{i=1}^{P} (m_{recyc,i} \cdot RCR_i)}{m} \cdot 100 \quad [\%]$	R^{*}_{cyc} = Recyclability rate [%] m = total product mass [kg] $m_{recyc,i}$ = mass of the ith recyclable part [kg] RCR_i = recycling rate of the ith part [%] P = number of recyclable parts
recoverability	$R_{cov} = \frac{\sum_{i=1}^{Q} (m_{recov,i} \cdot RVR_i)}{m} \cdot 100 \quad [\%]$	R_{cov} = Recoverability rate [%] m = total product mass [kg] $m_{recov,i}$ = mass of the ith recoverable part [kg] RVR_i = Recovery rate of the ith part [%] Q = number of parts that are recoverable

In the formula, the term "recyclability rate" (R^{*}_{cyc}) refers to the recyclability of the product. The rates RCR_i used for the product parts are called "recycling rates". We adopted, for this study in the context of eco-design, this distinction between "recyclability"/"recoverability" and "recycling"/"recovery" rate. To clearly distinguish from the recycling and recovery rates (RRR) measured by the operators of WEEE treatment facilities and the WEEE compliance schemes to comply with the reporting requirements of the WEEE directive, the term "calculated material-specific RRR" is used in the study to refer to the recycling and recovery rates of the parts (RCR_i).

2.2 Objectives of the reference values

The primary purpose of the reference values is primarily to support the development of product policies aiming at improving the recyclability of products and the resource efficiency. The database can provide the required data for a harmonized methodology how to calculate recylability and recoverability rates for example to be used in the preparatory studies of the European Ecodesign Directive [22], as well as transparency on data quality and availability.

The setting-up of reference values on RRR to support the calculation of recyclability and recoverability rates of products would address some of the critics on the methods used to calculate mass-based recyclability and recoverability rates of products [11], [23]. For instance, the method to define the reference networks of economically viable recycling processes (which may strongly vary in time) is precisely defined, and the data on treatment networks are collected, processed, saved and updated in a systematic, consistent and standardised way. Because the lack of harmonization for the calculation method of RRR currently leads to ambiguities to calculate the recyclability and recoverability rates of products, the calculation of the reference values needs to be linked to current standardisation efforts. These include the development of the generic standards on reusability/ recyclability/recoverability indexes by the European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (Cenelec) and European Telecommunications Standards Institute (ETSI) [24]. Beyond the calculation of recyclability and recoverability rates, the database aims at offering the possibility to address the specificities of (critical) trace materials with a low mass that hardly influences the recyclability rate, and further parameters like the quality of produced secondary raw materials.

The reference values supports the comparison of mass-based recyclability and recoverability rates of products or product groups based on the bill of material. Non material-related design factors (like connections within the product, see also section 6.1.1, p. 101), economic constraints and other factors influencing the recyclability and the environmental benefits of recycling and recovering different materials are not captured in the database. The database alone cannot support product designers in their holistic efforts to find the most suitable and environment-friendly design solutions. It cannot replace a detailed and simulation-based assessement of the recyclability of a particular product, as presented by Reuter & van Schaik [25].

2.3 Applicability for other methods and standards

The calculation of recyclability and recoverability of products is part of the scope several methods and standards. The technical report IEC/TR 62635 provides a methodology "for calculating the recyclability and recoverability rates" [12], which was used as a basis to refine the REAPro method [6]. The OECD Sustainable Manufacturing Toolkit recommends to calculate a recyclability indicator [13]. A further source of methodological information is the technical rule PAS 1049 "Transmission of recycling relevant product information between producers and recyclers - The recycling passport" [14].

One criterion of the rating system for greener electronics EPEAT is "design for end of life" (see also IEEE 1680 Family of Standards for Environmental Assessment of Electronic Products [15]). Following issues are addressed (Section 4.3 "Design for end of life" of the EPEAT Conformity Assessment Protocol [16]):

1. Ability to disassemble product
2. Recyclability of plastics
3. Materials with special handling needs
4. Planning and analysis for end of life, in which the calculation of the indicator "reusable/recyclable percentage", defined as the weight of materials that is recyclable, divided by the total weight of the product, multiplied by 100, is required.

Table 4 shows whether reference values for RRR of materials/components for various electr(on)ic equipment categories could also be useful for the above mentioned approaches/standards. Table 4 shows that the information provided in the database can be used to assess the recyclability according to various approaches, or to provide necessary information about the recyclability of product (parts) for product designers and manufacturers, WEEE treatment companies, legislative processes and labelling.

Table 4: Standards and approaches for recyclability

Standard/ Approach	Title	User (purpose)	Scope	Recyclability as defined in approach	Reference values applicable
IEC/TR 62635	Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment	Manufacturers (Provision of information for recyclers)	Electric and electronic equipment	Ratio of recyclable product mass to total product mass	Yes
MEErP method including the Material-efficiency Ecodesign Module for future studies related to the implementation of the ErP directive		European Commission (ErP Directive)	Energy related products according to http://www.eup-network.de/product-groups/overview-ecodesign/	Recyclability benefit rate depending on the mass fractions of materials considered as re-used, recycled and recovered	Yes
PEF	Product Environmental Footprint (PEF)	Any user calculating the environmental footprint of products	Any good or service	"Recycling rate of material" is the proportion of material in the product that will be recycled in a subsequent system	Limited (Depending on requirements for data quality and assumptions about used processes (e.g. BAT or average state)
CEN/TS 16524:2013	Mechanical products - Methodology for reduction of environmental impacts in product design and development	Manufacturers (Provision of information for recyclers)	Mechanical products, including Electric and electronic equipment	Mass-based approach similar to the ReaPro method. Generic estimated recyclability rates for 6 material families are provided in the standard. If specific data are available to the company, they should be used.	Yes

Standard/ Approach	**Title**	**User (purpose)**	**Scope**	**Recyclability as defined in approach**	**Reference values applicable**
PAS 2049	Transmission of recycling relevant product information between producers and recyclers – The recycling passport	Manufacturers (Provision of information for recyclers)	Electric and electronic equipment	The Recycling-passport can include information on the recycling properties of the product, i.e. information about disassembly or recycling friendly product design.	Yes
IEEE 1680 and EPEAT Conformity Assessment Protocol	Standard for Environmental Assessment of Personal Computer Products, including Laptop Personal Computers, Desktop Personal Computers, and Personal Computer Monitors	Manufacturer, Institutional purchasers (public procurement)	Computer Products, including Laptop Personal Computers, Desktop Personal Computers, and Personal Computer Monitors	Product criterion: 65% (required)/90% (optional) or greater of materials and components by weight shall be reusable or recyclable within the current infrastructure and using demonstrated technologies.	Yes
OECD [13]	Sustainable Manufacturing Toolkit	Any business size, sector or country (Assessment of environmental performance)	Production processes or products	Proportion of products that is made up of recyclable materials	No
ISO 22628	Road vehicles - Recyclability and recoverability - Calculation method	Vehicle manufacturer	End of life vehicles	Percentage of the mass (material) of a new vehicle that can be recycled, potentially re-used or both	Limited (material based approach, so that electronic parts are not considered separately)

2.4 Scope of the reference values and classifications

The objective of this section is to define the scope of the database in terms of treatment chain (treatment chain considered in the calculation of the rates) and product parameters.

2.4.1 Treatment chain

The WEEELABEX standard [18], which was developed in co-operation with stakeholders from the producer community and processing industry, provides in annex D a harmonised method to calculate RRR, which can partly be used for producing the reference values. The requirements of WEEELABEX on the calculation of recycling and recovery rates were adopted in the standard EN 50625-1 [27] and are implemented in the software WF-RepTool, which is used by operators of treatment facilities to calculate and report their RRR.

According to the WEEELABEX standard, the whole treatment chain for collected WEEE needs be considered. As stated in article 5.7.5 of WEEELABEX [18], the determination process of recycling and recovery rates (RRR) starts with the untreated WEEE and ends when the end-of-waste status for fractions is achieved or with the final recovery or disposal of fractions, produced by treatment of the appliances of a WEEE input flow. The boundaries of the treatment chain defined in the WEEELABEX standard to calculate the RRR are used to calculate the reference values.

Only economically running treatment processes complying with the legislation, for instance the WEEE directive, are considered. Pilot or experimental processes are, in principle, excluded. An exemption of that can make sense to estimate the RRR for materials that are not contained yet in the collected WEEE and for which processes need to be considered that are still under development and that are expected to run economically in the future.

According to the technical report IEC/TR 62635 [12] and Mathieux, Froelich, & Moszkowicz [28], economically running processes imply that they are used by at least two industrial plants in operation in Europe. However, for material flows having low volumes, which may be the case when looking to the recycling of CRM, only one facility may use an economically running process, and it may operate outside Europe. The term "economically running processes" aim at excluding pilot or R&D processes, which are not established yet in the treatment industry.

Other possible criteria to define economically running treatment processes are:

- Having been run at industrial scale for at least one year and
- Being named by at least two European treatment facilities in the reporting conducted to calculate the RRR, as a process to which WEEE fractions are sent.

In the study, we considered that the reports compiled by the operators to calculate the RRR in the past years take only economically running processes into account.

2.4.1.1 Groups of treatment processes

Figure 1 shows the understanding of the WEEE flows in an EoL treatment chain used in the IEC/TR 62635 and in the REAPro method. The collected WEEE is first pre-treated, then the remaining fractions are separated. The outputs of pre-treatment and material separations go to additional treatment to produce e.g. reusable parts, recyclates, waste for energy recovery and residues for disposal.

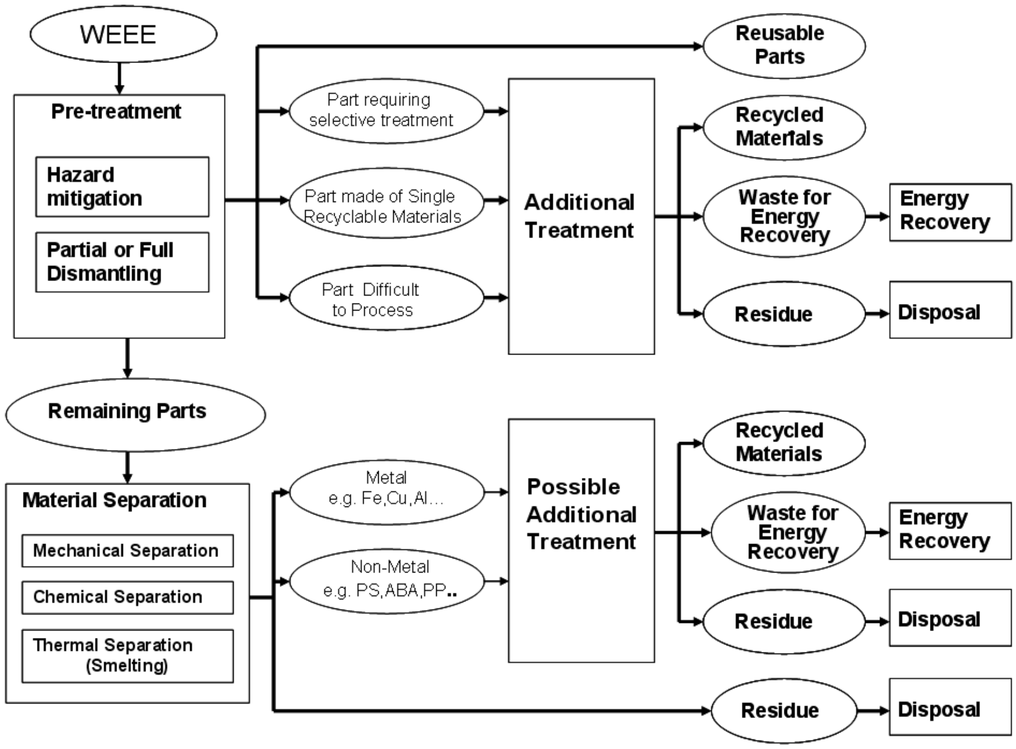

Figure 1: EoL treatment of WEEE according to IEC/TR 62635

The WEEELABEX standard encourages "the use of WF-RepTool, a web-based tool developed by the WEEE Forum that allows operators to report recycling and recovery rates on the basis of uniform definitions" [18].

In WF-RepTool, the treatment technologies are classified into two categories (see annex 3): interim and final technologies.

Interim technologies are in general separation (or conditioning[1]) processes where – a yield of – different output fractions are achieved (including preparing for re-use), whereas the final technologies aim at producing secondary raw materials (e.g. smelters), re-use appliances and components, and at treating output fractions by incineration and dispose them e.g. at landfill sites. WF-RepTool 'final technologies' are defined as 'final' processes where there is

- a changing of the physical characteristics of the waste fraction (e.g. metal smelting processes, incineration, including plastics recycling = granulation/compounding) or
- processes which can be quoted as 'final destinations' (e.g. concrete production, landfills) where the waste fraction will stay, at least for a long time period.

For fractions delivered to 'final technologies', data on the composition of fractions are requested in the WF-RepTool.

Figure 2 shows the structure of the WF-RepTool with main treatment steps and examples on output fractions achieved as to be further treated or delivered to final processes. The interim technologies are depicted in the "treatment chain" box and separated from the final processes. The input and output fractions are classified with 6

[1] e.g. crushing/grinding, cleaning, further separation

digit codes according to the structure given by the EWC, as explained in section 2.4.2.2.

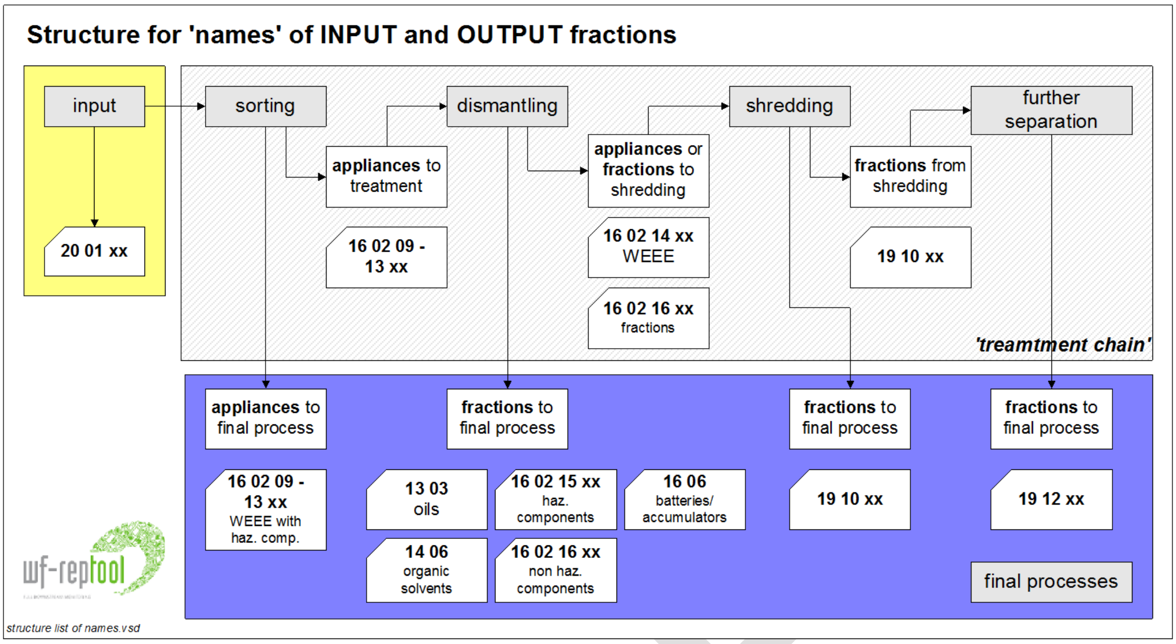

Figure 2: Input-output fraction structure according to WF-RepTool

For the reference values, we propose to use the classification of WF-RepTool distinguishing two groups of treatment processes:

1. Interim Technology
2. Final technology

The interim technologies include the groups "pre-treatment" and "material separation" of the REAPro method and IEC/TR 62635. The final technologies are the "additional treatment" of the REAPro method and IEC/TR 62635.

2.4.1.2 Interim technologies

Interim technologies aim at separating the materials contained in the input WEEE flows. In WF-RepTool, interim technologies are defined as separation (or conditioning) processes where – a yield of – different output fractions are achieved (including preparing for re-use). Interim technologies include dismantling / sorting, large shredder / separation, shredder for cooling & freezing appliances / separation, medium shredder / separation and special treatment of gas discharge lamps (see annex 3).

The material-specific performance of interim technologies regarding recycling and recovery is reflected by its ability to bring the input materials to output fractions that will be fed into the adequate final technologies. For example, the rate of the interim technologies related to copper recycling is measured as the mass of copper parts brought to fractions that will go to a copper smelter divided by the mass of copper contained in the WEEE input flow. The copper not forwarded to a copper smelter may be forwarded to facilities in which copper is not recycled, for example a facility intending plastic recycling or a steel mill.

2.4.1.2.1 First interim technologies

The first interim technology is the first treatment step of any WEEE input category. The first interim technologies generate output fractions that are either the input fractions to the final technologies as defined in section 2.4.1.3 or that are forwarded to further interim technologies for further separation. A list of first interim technologies is provided in the WF-RepTool classification list of technologies in annex 3. Some input flows might undergo no or very limited first interim technology. For example, small high-grade equipment like mobile phones can be fed after manual removal of the battery as complete devices into a metallurgical process [29].

2.4.1.2.2 Fraction-specific interim technologies

Some output fraction of the first interim technologies, like the complex parts cables and motors, are made of several materials. A further separation of the materials is required before entering the final technologies. Other fractions like plastics mix require conditioning. The RRR for these complex fractions need to take into account the performance of the fraction-specific separation or conditioning technologies to separate appropriate fractions for next interim or final technologies, e.g. (pure) copper fractions forwarded to copper smelters or plastics fractions forwarded to further plastics conditioning or final technologies like plastics recycling or incineration processes with energy recovery.

In WF-RepTool (annex 3), following processes are considered as fraction-specific interim technologies:

- special treatment process for compound fractions like cables (fine shredder)
- special treatment processes of gas discharge lamps, flat display panels or other components,
- special conditioning process like for plastics, glass, minerals, and wood. For some fraction, special fine shredders like cable shredders may be used.

2.4.1.3 Final technologies

The inputs to the final technologies are the outputs of the last interim technologies (first and fraction-specific interim technology, depending on the considered fraction). The final technologies aim at producing secondary raw materials, re-use appliances and components, and at treating fractions by incineration and dispose them e.g. at landfill sites. In WF-RepTool, the use of a final fraction in a final technology is classified as recycled, recovered or disposed (see section 2.4.1.3.1).

Final technologies are listed and classified in sections 2.4.1.3.2-2.4.1.3.4. This list will need to be adapted, updated and expanded during the construction of the reference values, depending on the materials that are contained in the products and on the state-of-the-art regarding treatment technologies.

2.4.1.3.1 Classification as recycling or recovery

In the WF-RepTool, the target use of any fraction / the component/s of any fraction in the final technology is the core element. This classification is provided in the WF-RepTool model classification [30] (annex 4), to which reference is set in the WEEELABEX standard. The classification of uses relevant for the reference values, for which re-use is, so far, not considered, is given by the Waste framework directive [21]:

- Recycled (abbreviation: R) – 'recycling' means "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It […] does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" [21]. The definition does not differentiate between functional and non-functional recycling (down-cycling).

- Recovered – 'recovery' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy [21].

For the calculation of the recovery rate the total of recovered is calculated as: Recovered = [RU +] R + OMR + ER

(abbreviations: RU: preparing for re-use, not considered in the feasibility study; OMR: other material recovery [31] with which the requirements for the classification as 'recycling' are not met (example: backfilling), and ER: energy recovery)

- Disposal means "any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy" [21] (abbreviations: TD: thermal disposal and LD: other disposal, mainly landfill disposal)

2.4.1.3.2Technologies intending recycling

Feeding fractions from the interim technologies to a final technology intending recycling does not automatically mean that they will be recycled. All treatment technologies generate residues that need to be disposed. Moreover, some fractions or shares of fractions may be fed to a final technology intending recycling with the purpose of recovering energy or achieving "other material recovery" (see section 2.4.1.3.3). Following technologies listed as final technologies in the WF-RepTool (annex 3) may be considered as intending metal recycling:

- Al smelter
- Cu smelter 'special'
- Cu smelter 'traditional'
- Pb smelter
- stainless steel works
- steel mill 'traditional'
- other metal smelters

Following technologies listed as final technologies in the WF-RepTool (annex 3) may be considered as intending the classification of the use of plastics as recycling:

- Production of plastics and granulates
- Feedstock substitution in production of other products of/with plastics
- Synthesis gas production

Also the production of oil binding material, of glass and of materials for road construction and defined construction purposes are included in the list of uses in example technologies of the WF-RepTool that may lead to the recycling classification of the use of the WEEE fractions (annex 4).

2.4.1.3.3Technologies intending recovery

In addition to the classification of the target use of a fraction as 're-used' (excluded from this study) or as 'recycled', two recovery categories of uses are distinguished in WF-RepTool: other material recovery (OMR) and energy recovery (ER).

Backfilling and other uses in technologies with which requirements for the classification as 'recycling' is not met (no products achieved) are examples for technologies where the use of fractions may be classified as OMR (annex 4). Feeding iron as reducing agent to a copper smelter is an example of OMR if the slag of the copper smelter is not classified as by-product or not used as/in a defined product, and the iron replaces other materials (the definition of 'recovery' is met, not the definition of 'recycling').

Examples of ER are co-incineration of plastics in business incinerators like cement kilns or in municipal waste incinerators with R1 classification (high energy efficiency) and the use of plastics/organic shares as fuel substitution in 'special' copper smelters or 'special' steel mills, for which the plant operators may approve a special plant technology to use plastics or organic shares for fuel substitution. Because the focus of the reference values is not energy recovery, so far it is planned to include into the database only information on the mass of the final fractions which use is classified as ER, and no further information like the amount of energy that can be potentially won out of this fractions.

2.4.1.3.4 Disposal technologies

'Disposal' means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy [21]. The WF-RepTool distinguishes 'hot technologies', including municipal waste incineration, hazardous waste incineration and the thermal disposal of organic shares in smelters with no dedicated use of plastics/organic shares, and 'cold technologies', including landfill and special landfill and in other technologies where no use of the fraction may be counted as recovery.

2.4.2 Product parameters

2.4.2.1 Classification at product level

In terms of EEE product classification, we propose to use the classification of EEE of Wang, Huisman, Baldé, & Stevels [32]. All EEE are grouped into ten primary categories, according to the EU WEEE Directive (with an extra category for central heating). These ten major product categories are broken down into 58 sub-categories as represented by the UNU-keys. The 58 UNU-keys classify all possible EEE (about 900 products). Annex 1 shows the classification, which is organized based on three essential perspectives: product type, waste management and legislative relevancy. The classification enables consistent comparison of performance between regions and compliance schemes, as well of comparison of research results, by aligning their classification systems with the classifications applied in trade statistics, custom authorities and national statistical offices. The 17 categories used by the WEEE Forum are compatible with the list.

The classification levels for the database shown in annex 1 (product categories, UNU-keys or products) can be used in a flexible way to find an acceptable compromise between precision of the reference values and activities needed to gather the data. This flexibility is mentioned in the Commission Implementing Decision C(2014) 10238 [24], which states that the tables about recycling and recovery rates of some specific materials and components "could be product-group specific" and, if feasible, "could be set at the product level and/or at product subset level".

2.4.2.2 Classification at material level

WF-RepTool [33] provides a list of output fractions (annex 2) from the last interim technologies (i.e. the final fractions forwarded to final technologies) that can be used as a basis to list and classify the materials used in EEE. The final fractions are split into their composition (different components with a certain weight share). The (target) use of each component in the final technology can be classified as recycling, recovery, or disposal (see Figure 3).

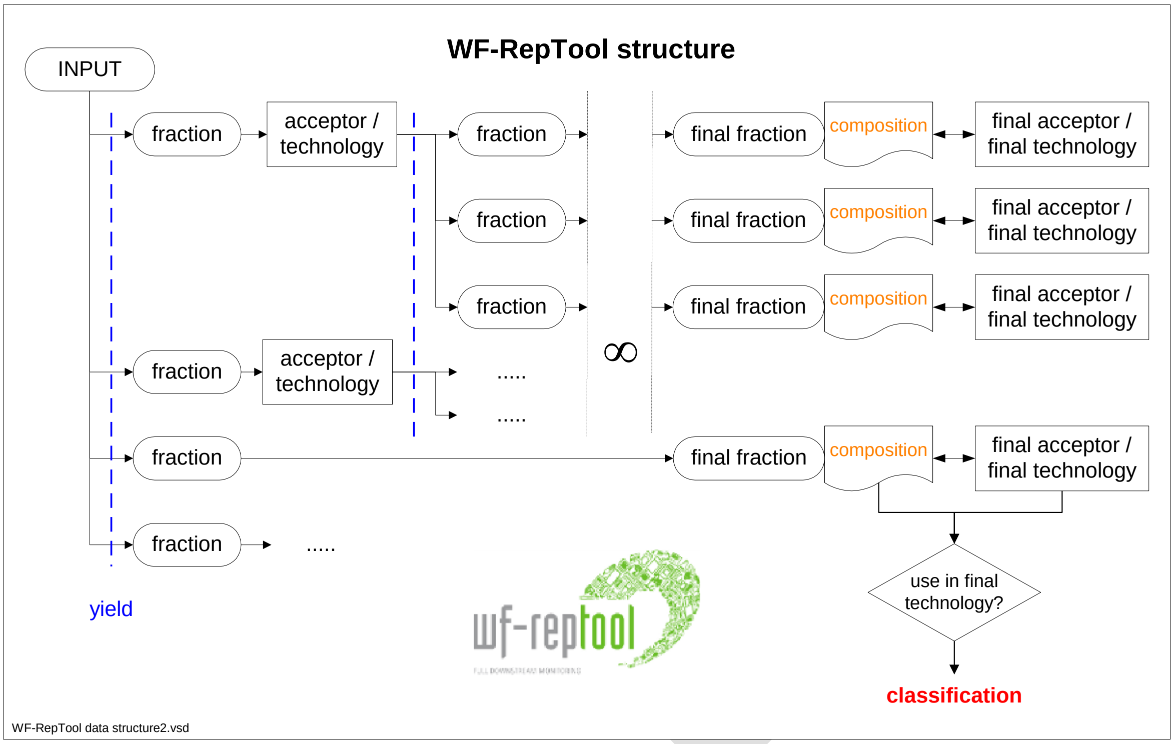

Figure 3: WF-RepTool tree-structure of treatment results [34]

Linking the classifications of materials in products and the classification of the use of the final fractions as recycling or recovery facilitates the calculation of the recyclability and recoverability rates of products when applying appropriate EoL scenarios.

The WF-RepTool list of output fractions (annex 2) is structured on the base of the European List of Waste, also called 'European Waste Catalogue' (EWC) [35] applying the rules of the EWC on the use of the EWC codes and the 6-digit codes provided by the EWC. For the multitude of output fractions from WEEE treatment in daily practice, sub-codes have been foreseen. The marking of hazardous materials with an asterisk (*) has been taken over from the EWC.

The WF-RepTool list of output fractions covers the requirements on selective treatment out of the Annex VII of the WEEE-Directive [36] and builds up on knowledge regarding possible fractions from WEEE treatment, distinguishing fractions from dismantling (mainly 16 xx xx), fractions from shredding (19 10 xx) and from further separation of fractions (19 12 xx). WF-RepTool list of output fractions, presented in Annex 2, lists about 400 fractions from WEEE treatment, including for example "(mix of) 'dry' batteries", "aluminium fraction 'pure'", "cable fraction", "printed circuit boards from dismantling - medium quality" or "mix of flat panel display 'modules'".

After elimination of the codes of output fractions designating:

- output fractions that were wrongly allocated to WEEE,
- process losses and other materials that cannot be found in new devices for which the recyclability should be calculated,
- materials used in technologies that are assumed not to be employed anymore in new products, for example cathode-ray tubes,
- materials which use is banned or restricted by the legislation (for instance RoHS directive), for example plastics parts above ROHS/REACH values for restricted brominated flame retardants and/or heavy metals,

the materials and components used in EEE were classified in the categories listed in Table 5.

Table 5: Classification of the materials and components used in EEE

Material and components	**Correspondance to WF-RepTool output fractions**	
	code	**Name of the fraction**
Iron	16 02 16 / 01	iron-rich' fraction from dismantling
	16 02 16 / 02	iron-metals 'pure' from dismantling
	19 12 02 / 01	iron fractions for further separation or for 'final processes'
Stainless steel	16 02 16 / 08	stainless steel 'pure' from dismantling
	19 12 02 / 02	stainless steel fractions for further separation or for 'final processes'
Aluminium[2]	16 02 16 / 03	aluminium-rich' fraction from
	16 02 16 / 04	dismantling aluminium-metals 'pure' from dismantling
	19 12 03 / 03	aluminium fractions for further separation or for 'final processes'
Copper[2]	16 02 16 / 05	copper-rich' fraction from dismantling
	16 02 16 / 06	copper-metals 'pure' from dismantling
	19 12 03 / 05	copper fractions after further separation for 'final processes'
Zinc[2]	19 12 03 / 07-3	zinc 'pure'
Rare earths	19 12 11* / 04-9	rare earths containing fractions
Mercury-containing parts	16 02 15* / 01-2 19 12 11* / 05	mercury containing ‘parts’ dismantled mercury containing fractions
High-grade printed circuit boards	16 02 15* / 02-1	printed circuit boards from dismantling – high quality
Medium-grade printed circuit boards	16 02 15* / 02-5	printed circuit boards from dismantling – medium quality
Low-grade printed circuit boards	16 02 15* / 02-3	printed circuit boards from dismantling – low quality
Printed circuit boards	19 12 11* / 08-2	circuit board fraction
Cables	16 02 16 / 10	cables (mix)
	19 12 03 / 08-2	cable fraction
Motors	16 02 16 / 11	electric motors/dry transformers (mix)
	19 12 03 / 01-3 19 12 03 / 01-4	motors/transformers after shredding
Compressors	16 02 16 / 12	compressors (excl. oil)
Drives	16 02 16 / 17	hard discs, cd-rom-, dvd- and floppy drives
Lamps	16 02 16 / 19	lamps - no hazardous substances
ABS	19 12 04 / 03-1	plastics 'pieces' ABS 'pure'
PS	19 12 04 / 03-2	plastics 'pieces' PS 'pure'
PE/PP	19 12 04 / 03-3	plastics 'pieces' PE +/- PP
PVC	19 12 04 / 03-4	plastics 'pieces' PVC 'pure'

[2] Aluminium, copper, zinc and other non-ferrous metals may also be included in ‘mixed’ non-ferrous metal fractions

Material and components	Correspondance to WF-RepTool output fractions	
	code	Name of the fraction
PU foam	16 02 11* / 02	mix of 'cabinets' containing PU foam insulation
	19 12 04 / 05-1a	PU foam < 0.2 % (H)CFC
	19 12 11* / 01	PU foam > 0.2 % (H)CFC
Other plastics parts	16 02 15* / 04	Plastics 'parts'
	16 02 16 / 30	
	16 02 16 / 31	
	19 12 04 / 03-5	other specific kinds of plastics 'pieces'
Plastic/metal-compounds	19 10 05* / 04	metal/plastics mixtures
	19 10 05* / 05	plastics/metal mixtures
Flat panel display	16 02 15* / 08-2a	LC flat panel display 'panels'
Glass	16 02 15* / 08-3	glass 'parts' from flat panel displays
	16 02 16 / 32	flat glass 'parts'
	16 02 16 / 38	glass 'parts' from flat panel displays
	19 12 05 / 01	glass 'pieces' 'pure'
	19 12 05 / 05	glass 'pieces' from flat panel displays
Wood	16 02 16 / 34-2 16 02 16 / 34-3	wood 'parts'
	19 12 07	wood 'pieces' 'pure'
Concrete	16 02 16 / 36	concrete 'parts' from dismantling
	19 12 09 / 02	concrete 'pieces'
Oil and liquid fuels	13 19 02 07*	Oil wastes and wastes of liquid fuels oil and concentrates from separation
Chlorofluorocarbons, HCFC, HFC	14 06 01*	chlorofluorocarbons, HCFC, HFC
Other organic solvents, refrigerants and propellants	14 06 02*, 14 06 03*	other halogenated solvents and solvent mixtures, other solvents and solvent mixtures
Toner cartridges, ink cartridges and ink ribbons	16 02 15* / 03	mix of toner cartridges, ink cartridges and ink ribbons
	16 02 16 / 37	toner cartridges
Lead batteries	16 06 01*	lead batteries
Ni-Cd batteries	16 06 02*	Ni-Cd batteries
Mercury-containing batteries	16 06 03*	mercury-containing batteries
Alkaline batteries	16 06 04	alkaline batteries (except 16 06 03)
NiMH batteries	16 06 05 / 01	NiMH batteries
Li-ion batteries	16 06 05 / 02	Li-ion batteries
Other batteries	16 06 xx(*) / 01-3 (open)	other specific kinds of batteries
Other material	16 02 15* / 20 (open) 16 02 16 / 80 (open)	other components/fractions from dismantling or sorting

2.4.2.3 Collection of data on product composition

Gathering data on the average material composition of electronic products is a challenge, because the use of materials is continuously adapted by the manufacturers to put attractive products onto the market, to respond to the demand of consumers (product types, functions) and to react to technological innovations.

Bills of materials were published in the preparatory studies using the Methodology for Ecodesign of Energy-related Products conducted in the framework of the Ecodesign Directive. Further attempts to collect, summarise and publish general data on the material composition of WEEE were done by research groups [37]–[44]. Many other publications made data on specific parts or components, like for flat displays [45] or LED-containing products [46]. Also the manufacturers of electronic products and components are involved in activities aiming at publishing data. Following initiatives can be named:

- Definition of umbrella specifications [47]
- Publication of material data sheets [48]
- Publication of ILCD Datasets [49]

A detailed analysis of literature was performed for the selected case studies in the methodology testing (section 3.2.2).

2.5 Definition of the EoL scenarios

The end-of-life scenario summarizes for a considered WEEE input flow the treatments that each appliance and part of appliance will undergo [6]. In other words, the end-of-life scenario summarizes the hypotheses that need to become reality for the recyclability rate to become a recycling rate [50].

To define the EoL scenario, Ardente & Mathieux [51] produced a generic "scheme of the EoL treatments of washing machines" (Figure 4). The generic scheme is presented in more detail in the report, distinguishing 're-usable parts', 'parts for selective treatments', 'parts for selective recycling', 'parts difficult to process' and 'other parts (for material separation)'. The generic scheme of Ardente & Mathieux [51] does not represent the final technologies.

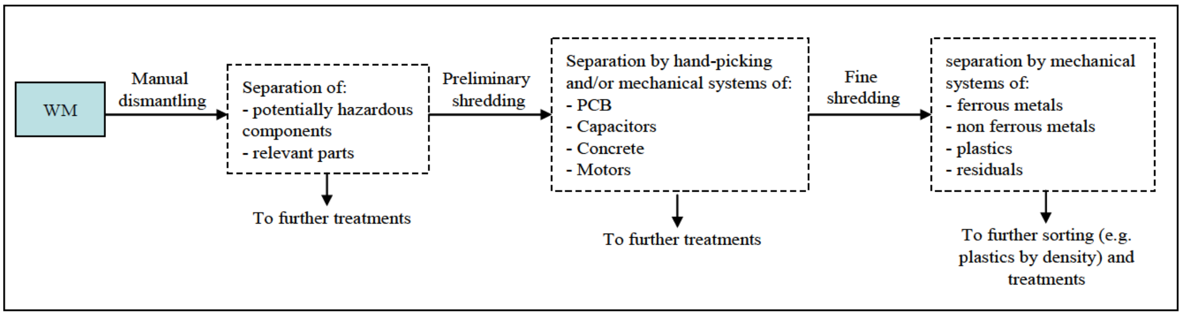

Figure 4: Scheme of the EoL treatments of washing machines [51]

This approach of first defining a generic scheme of the EoL scenario was adopted. The generic scheme covers the whole treatment chain for collected WEEE starting with the untreated WEEE and ending when the end-of-waste status for fractions is achieved or with the final recovery or disposal of fractions. This generic end-of-life scenario should apply to several selected operators. It is not too detailed, because the specific treatment technologies used to treat the WEEE (e.g. crushing technologies like shredders or smashers, separation technologies for plastics), as well as the order in which the technologies are used, can vary according to the operators. The generic EoL scenario is a reference network of economically running treatment processes.

Ardente & Mathieux [6] recommend that the EoL scenario should be set on the basis of a survey of the suitable EoL treatments and complemented by information from manufacturer and recyclers.

The main sources of data available to define the EoL scenario are:

- The methodological expertise and the data on recovery and recycling rates for WEEE reported using the WF-RepTool [33]
- Treatment standards, including [18], [27], [52], [53]
- Treatment processes and case studies described in the scientific literature
- Visits in treatment plants and interviews of operators

The following sections present the specificities of selected interim and final technologies regarding the data collection to calculate the RRR.

2.5.1 Interim technologies

The treatment technologies used by the operators are not very detailed in the reporting of the recycling and recovery rates for the treatment chain provided to Eco-systèmes, e.g. a first step treatment facility including manual and mechanical crushing and sorting technologies is usually represented as a single process. As long as the interim technologies used comply with the generic scheme of the EoL scenario, more information on the treatment technology is not necessary for the calculation of the material-specific RRR (as long as the data was checked for plausibility). This reduces the efforts necessary for collection data and the concerns related to confidentiality that may be raised.

Data necessary for the calculation of the RRR is the list of all output fractions of the interim technologies as final fractions being delivered to final technologies, their mass, their composition (e.g. in terms of metal content) and their destinations.

2.5.2 Final fractions and final technologies

2.5.2.1 Plastics

Plastics make out a large share of the WEEE flow and have a complex composition, due to the diversity of the polymers and additives used in EEE [39], [54], [55]. This results in technical and economic challenges to sort, separate and condition the plastics in a way enabling the production of recyclates with a quality fulfilling the market requirements.

Currently the level of detail (granularity) in the reporting of the RRR provided by Eco-systèmes does not allow a detailed differentiation between different types of plastics (e.g. between thermo- or duroplastics or even more detailed between resins like PU from PE, section 5.3.1). The evolution of normative requirements on plastics containing brominated flame retardants and the improvement of sorting technologies and downstream traceability may lead to a variation in the RRR reported on plastics [56].

2.5.2.2 Integrated smelters

Integrated copper smelters use a combination of pyro- and hydrometallurgical processes to recover precious metals, copper and other non-ferrous metals, including certain critical metals, while isolating hazardous substances. This process involves the integration of a copper smelter, a lead smelter (both pyrometallurgy) and hydrometallurgical metal recovery (leaching and electrowinning). For example, the facility of Umicore Precious Metals Refining is able to recover silver, gold, platinum, palladium, rhodium, iridium, ruthenium, indium, selenium, tellurium, antimony, tin, bismuth, lead, copper and nickel [57]. Copper smelters apply a combination of pyro- and hydrometallurgical processes to recover the main product copper cathodes. Copper smelters use copper scrap, WEEE, and primary copper ore concentrate as input into the smelting process [58].

The 'Standard on End-Processing of WEEE Fractions', 'Part I: Copper and precious metal containing fractions' developed by the European Electronics Recyclers Association and Eurometaux defines management requirements, technical requirements and requirements regarding monitoring and reporting in particular for the processing of copper and precious metal containing WEEE fractions [52]. Section 9.2 addresses the calculation of the RRR and provided a classification of the uses of the final fractions as recycling, energy recovery and disposal. The classification is currently updated in the frame of the discussion aiming at publishing the technical specification TS 50625-5 'Specification for the endprocessing of WEEE fractions – copper and precious metals'. In accordance with the WF-RepTool model classification [30] and with the Waste framework directive [21], the TS 50625-5 uses the terms recycling, other material recovery, energy recovery and disposal to classify the uses of the final fractions for the calculation of the RRR.

In the "Declaration of Aurubis AG, D-44532 Lünen, in the range of processing secondary copper and precious metals bearing raw materials, such as electronic scrap" [59], the operator Aurubis of a pyrometallurgical process proposes following classification of the uses of the fractions:

1. Use of plastics present as composite materials (e.g. PCB material): recovery of the organic content of composite materials is defined as 50% other material recovery for the use as reducing agent and 50% energy recovery for the use as fuel substitute.
2. Iron and aluminum contents of WEEE fractions are used in the pyrometallurgical process as reducing agent and as a slag forming components. The iron silicate sand is marketed for various construction applications, as an abrasive etc.
3. Metal-specific recycling rates: the process has the following minimum recycling rates for the following metals:
    - Copper: >90% (product: copper cathode)
    - Silver >90% (product: silver (as metal))
    - Gold >90% (product: gold (as metal))
    - Palladium >90% (product: platinum group metal solution)
    - Lead >90% (product: lead tin alloy, anode mud, KRS-oxide)
    - Tin >75% (product: lead tin alloy)
    - Nickel >90% (product: nickel sulfate)
    - Antimony >80% (product: Lead dross (Sb rich), speiss)
    - Further metal contents like bismuth, selenium and tellurium are recovered.

Table 6 and Figure 5 show the metal-specific recycling rates published in the literature [58], [60]. The rates are consistent with the declaration of Aurubis for copper, silver, gold and palladium (recycling rate over 90%), but deviations can be observed in Figure 5 for the other recovered metals (lead, tin, nickel, antimony). So far, reliable and updated data on the metal-specific recycling rates are not available for the assessment of the recyclability concerning lead, tin, nickel, antimony, bismuth, selenium, tellurium and other metals considered in the references [58], [60] and/or [59].

Table 6: Metal-specific recycling rates in different high efficient pyrometallurgical operations, compiled by CRI [58] based on data from Umicore (Hoboken, Belgium), Boliden, Rönnskar (Skellefteham, Sweden) and Aurubis (Hamburg/Lünen, Germany)

	Integrated smelter	Copper smelter:
Ag	> 95 %	95 %
Co	90 %	(90 %)
In	< 50 %, partly to slag	0 % residue
Li	0 % slag	0 % slag
Ta	0 % slag	0 % slag
Te	> 90 % recovered from Cu-alloy	80 %/ (90 % as Copper-Telluride)
W	0 % slag	0 % slag
Au	> 95 %	95 %
Be	0 % , lost in Cu-alloy or slag	0 % , lost in Cu-alloy or slag
Ga	0 % fly ash/slag	0 % fly ash/slag
Ge	0 % fly ash/slag	0 % fly ash/residue
Pd	> 95 %	95 % / (90 % as concentrate)
Ru	95 % (selective pre-processing assumed)	90 % / (90 % as concentrate)

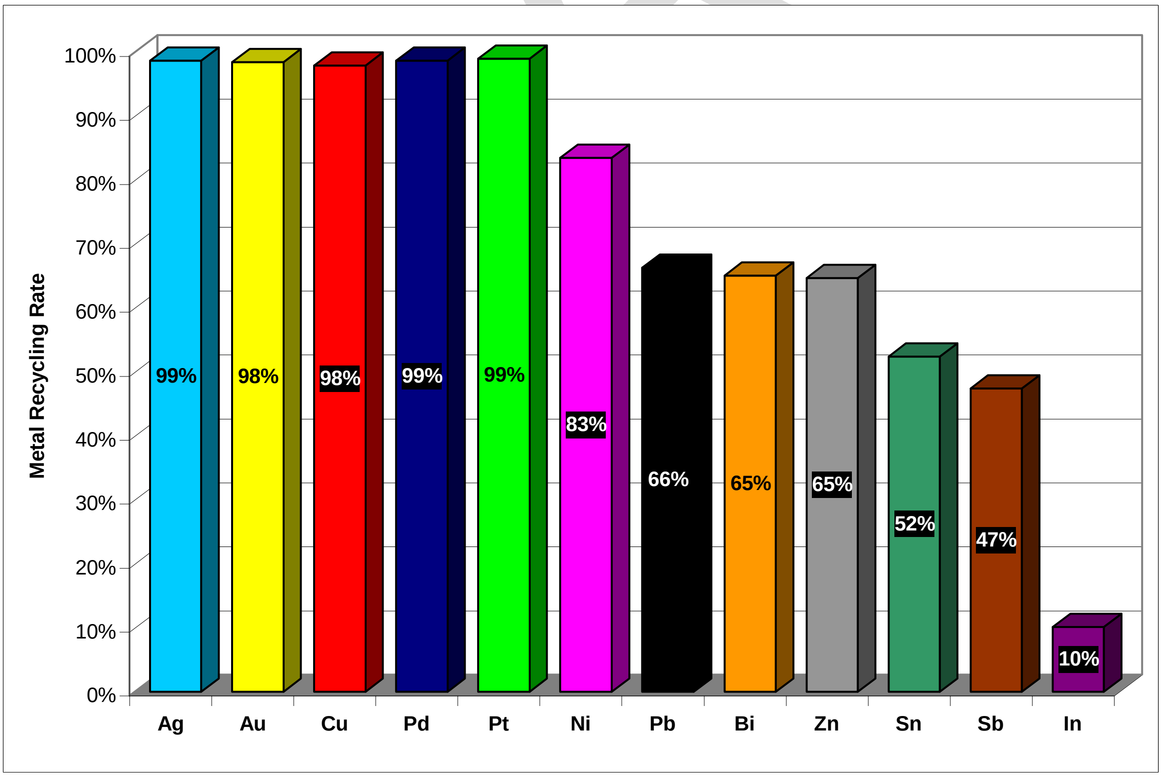

Figure 5: Overall average metal-specific recycling rates of copper fraction treatment in smelters (100%: input into copper smelter). Compiled by Deubzer [60]

In the feasibility study, Aurubis supported the calculation of the RRR for PCB by providing expertise on the products of the Aurubis integrated smelter and their classification as "recycling", "other material recovery" and "energy recovery". In accordance with the WF-RepTool model classification [30], the recovery of the plastics in an integrated smelter was defined as 50% other material recovery for its use as reducing agent and 50% energy recovery for its use as fuel substitute. The used methodology is based on the requirements on the calculation of the RRR discussed and harmonised during the development the EERA/Eurometaux standard [52].

2.5.2.3 Critical raw materials

In this study, CRM are defined as being parts of the list of CRM published by the European Commission [61]. Table 7 presents a screening of the CRM, their relevance in electronics and for the feasibility study.

Table 7: Screening of the relevance of critical raw materials for the study

CRM according to EC 2014	**Relevance in electronics: if yes, in which applications?** [62]	**Relevance according to UPgrade research** [37]	**Potentially relevant for feasibility study?**
Antimony	Yes, flame retardants	Yes, flame retardants	Yes, with limitations
Beryllium	Yes, electric/ electronic connectors	Not considered	Not recommended
Borates	Yes, glass of LCDs, in a small extent in flame retardants	Not considered	Not recommended
Chromium	Yes, stainless steal	Not considered	Not recommended
Cobalt	Yes, Li-ion and NiMH batteries	Yes, batteries	Yes
Coking coal	No		
Fluorspar	No		
Gallium	Yes, LEDs and integrated circuits (ICs)	Yes, ICs	Yes, with limitations
Germanium	Yes, LEDs and electronic components	Yes, but no data available	Not recommended
Indium	Yes, LCD panels, in a minor extent also LEDs, solders and semi-conductors	Yes, LCD panels	Yes
Magnesite	No		
Magnesium	Yes, casings	Not considered	Yes, with limitations
Natural Graphite	Yes, Li-ion batteries	Not considered	Not recommended
Niobium	Yes, some magnets	Not considered	Not recommended
PGMs	Yes, palladium in electronic components/printed circuit boards, Pt and Ru in hard disk drives, iridium in LEDs	Yes, palladium in electronic components	Yes

CRM according to EC 2014	**Relevance in electronics: if yes, in which applications?** [62]	**Relevance according to UPgrade research** [37]	**Potentially relevant for feasibility study?**
Phosphate Rock	No		
REEs (Light and Heavy)	Yes, magnets in motors, drives and loudspeakers, NiMH batteries, phosphors of CCFL and LED backlighting systems	Yes, magnets in motors, drives and loudspeakers, and in NiMH batteries	Yes
Silicon metal	Yes, silicon semiconductors in chips	Not considered	Not recommended
Tungsten	Yes, hard metal alloys for tools, filaments for lighting equipment	Not considered	Not recommended

In this study, it was decided to set a special focus on cobalt from batteries, indium from LCD panels and palladium from PCB with their components.

2.6 Methods for data collection

2.6.1 Options to calculate the material-specific RRR

To quantify the recyclability and recoverability rates of products put on the market based on the recycling and recovery rates of the contained materials and components, which are achieved by the operators using a process chain complying with the EoL scenario, several options are possible and combinable:

1. Use data on RRR compiled using the WF-RepTool for WEEE input flows with which products/appliances would be treated. The data is collected based on batch analyses and need to be checked and validated. To calculate the material-specific RRR, analyses on the input composition are combined with the shares of final fractions classified as recycled and recovered, reported through WF-RepTool.
2. Conduct additional batch analyses at treatment operators, i.e. analyse the input and the output of treatment processes. In doing so, it is important to consider the whole treatment chain (all interim and final technologies, see section 2.4.1). The analysis can be done e.g. in the frame of research projects or combined with other goals, e.g. certification processes.
3. Model the processes with simulation tools like the one presented by Reuter and van Schaik [25]. This requires validating the WEEE input flow and process-related parameters through experimental analyses.

In the feasibility study, the focus was set on option 1. One reason is that the use of data that are collected anyway in the frame of the reporting for the national WEEE regulations transposing the WEEE directive by using harmonised methods may decrease the activities required to produce the reference values. Another reason is related to doubts on the validity of RRR estimated for a theoretical end-of-life scenario. In other words, we opted for the use of data measured with standardized methods instead of modelling or estimation results.

Option 1 is linked with the two other options. Deeper or additional batch analyses (option 2) can complete the available data to get more information, e.g. on the composition of the input and/or to gather more disaggregated RRR (for instance: by plastic type).

Also option 3 can be very useful, e.g. to analyse the effects of product design on the performance of the treatment chain. The effects of the design of individual products on the recyclability and recoverability depend on the treatment technologies considered and the order in which they are combined. By changing the parameters modelling the treatment processes, these effects may be systematically investigated for a holistic understanding of the factors influencing the recyclability, which is hardly possible using the option 1 and 2. However, the simulation tools of option 3 require detailed information on representative end-of-life scenarios and representative input flows to set the simulation parameters. This information reflecting the diversity of the treatment technologies used in Europe, as well as the complexity of the WEEE input flows, keeping in mind that the products cannot be treated separately with batches of each product-type (it may be the case only for some very "rich" products or in very specific collection schemes), is not available [63].

2.6.2 Use of the data on recycling and recovery rates

As explained in section 2.4.1, the definitions, methods and rules adopted in the WEEELABEX standard [18] serve as a basis to set the frame to define for instance the reference network of economically running treatment processes, which is a key element to define the scope of the calculation of recyclability and recoverability rates.

The data on RRR compiled using the WF-RepTool are currently not publicly available. The original data based on the results of the batch analyses are stored by the operators and/or by the WEEE compliance schemes, where they are aggregated to comply with the reporting requirements of the national authorities, which report national RRR to the European Commission [64].

2.6.2.1 Aggregation of data on recycling and recovery rates along the treatment chain

End-of-life scenarios (section 2.5) consist of a chain of interim and final treatment technologies. Many fractions produced by interim technologies require additional downstream operations (and operators) to produce end-of-waste fractions (products or recyclates) and other fractions which use in the final technology is classified as recovered or disposed. The quality of the output fractions from the first step process(es), depending on the used technologies, usually influences the following downstream processes (adequate technologies to be used, performance of the processes). For example, the quality of a mixed fraction of plastics and non-ferrous metals produced by a step-1 operator influences the quantity and the quality of the three fractions sorted by the step-2 operator: 1) a "non-ferrous metals" fraction, 2) a "plastics" fraction, and 3) losses/waste. This interdependence is true for most, but not for all fractions, i.e. it would be feasible and realistic to consider separately the first (sorting) step and the second and last step for some fractions that usually do not require intermediary sorting steps before their final treatment, e.g. PU foams after the shredder for cooling & freezing appliances [63].

Due to the frequent interdependence between the steps, a WEEE treatment chain from the first to the last processes should be considered as a whole, i.e. including all interim and final treatment technologies (option 2 presented in Figure 6) and not to consider separately each treatment step (option 1 of Figure 6). In other words, the calculation of the RRR should be based on the whole process chain and not on an analysis of the specific rates achieved by each step of the treatment chain.

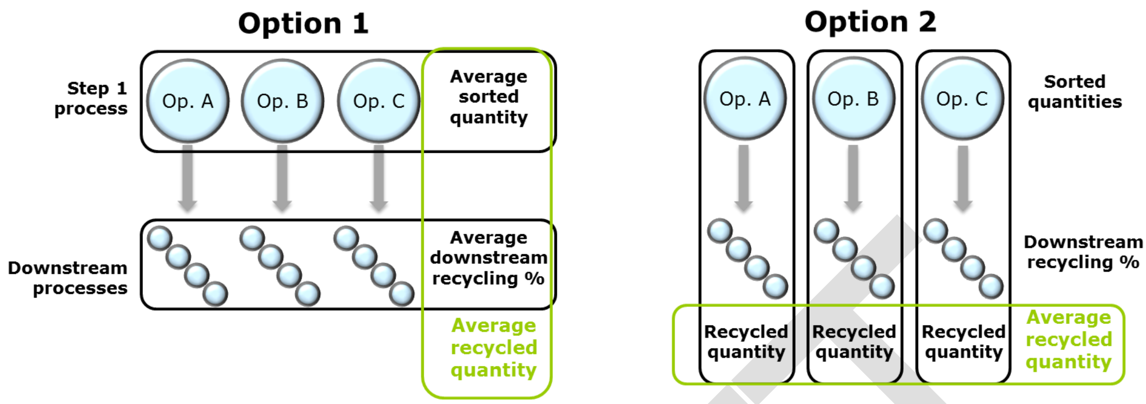

Figure 6: Possible methods to aggregate multi-operators / multi-steps assessments (op.: operator) [65]

The reports on the RRR using WF-RepTool do not necessarily detail the treatment technologies that are used by each operator along the treatment chain. The WF-RepTool recommends to use a stepwise approach to report each 'area' of treatment steps (e.g. (1) dismantling, (2) shredding/separation and (3) further separation of fractions) [66]. If several treatment steps of shredding and/or separation are applied in one 'area', these treatment steps may be aggregated and fractions leaving the 'area' have to be reported. A black box approach for the facility may be applied in case of small operators, e.g. a first step treatment facility including manual and mechanical crushing and sorting technologies may be represented as a single process. At least each operator with his treatment technology (with a headline term for the technology) should be separately considered in the WF-RepTool. The black box approach of reporting only the fractions leaving the 'whole facility' reduces options of plausibility control and transparency. The black box approach of reporting only the fractions leaving the 'whole treatment chain' reduces even more drastically the possibility of plausibility control and transparency [66].

The compliance of the total treatment chain used by the operator including all interim and final technologies with the generic scheme of the EoL scenario considered for the calculation of the RRR must be checked by experts that know in details the operator and its treatment chain. Some of the information on treatment technologies needed for the check may be confidential (section 5.2.4).

2.6.2.2 Selection of the panel of operators

One key question is the level of treatment quality that should be reflected by the RRR. For instance, do the RRR reflect the average treatment chain, or the best available techniques (BAT)?

The concept of retrieving RRR from operators using economically running BAT is justified by the idea that recyclability aims to consider the treatment processes applied at the time at which the product becomes waste, i.e. some years after having been put onto the market. We hope and assume that the BAT of today will be at least the average technologies of tomorrow. Considering BAT for calculating the RRR should encourage the stakeholders (producers, treatment operators and public authorities) to ensure that BAT become soon the average treatment techniques. For the calculation of the RRR, BAT do not include technologies in research and development stage that are not (yet) economically running. Because, due to economic, technical and environmental conflicts, treatment processes cannot be optimized simultaneously for all fractions, the BAT consider real whole treatment chains including interim and final technologies and not a virtual combination of best techniques available for every step (calculation according to option 2 and not option 1 of Figure 6).

Possible approaches to decide over the number of operators to be selected to calculate the material-specific RRR achieved by an EoL scenario for a defined WEEE input flow are:

- To fix the number of first step operators achieving the highest RRR[3] with their downstream acceptors (e.g. three like in the case studies presented in section 3.2)
- To select a percentage of the operators for which data are available (e.g. 50% of the first step operators achieving the highest RRR with their downstream acceptors)
- To take all operators and calculate an average (no BAT approach).

The more operators are selected for the calculation of the material-specific RRR, the better for the data validity and the statistical analysis – however, if all available operators were selected, the resulting RRR would not represent the BAT, but the average state-of-the-art. Therefore, a compromise is needed to consider enough operators for a satisfying validity, but also to consider BAT instead of average technologies.

In addition to the selection criteria related to performance measured by the RRR, the selection of the operator panel should be linked to the share of the treated WEEE flow (market share) to avoid selecting a little representative panel of operators treating low volumes of WEEE. For that, several representativeness criteria could be introduced, such as all selected operators should together treat at least e.g. 30-50% of the WEEE treated by all operators for which data are available, the processes are economic viable and the technologies used are representative for the treated WEEE stream.

The number of selected operators, as well as the criteria to select them, can differ according to the WEEE flows, depending e.g. on the total number of operators treating this specific WEEE flow for which data on RRR are available.

2.7 Method to calculate the material-specific RRR for a product or product group

The reference values refer to the calculated material-specific RRR for the materials contained in the WEEE input flows. The materials are listed in Table 5, page 28 (e.g. stainless steel, high-grade printed circuit boards, ABS or wood).

The proposed method is illustrated by Figure 7. The material-specific RRR are calculated based on data on the input WEEE flow into the treatment processes and the mass of the shares of the final fractions, which use is classified as recycled and recovered. The mass and shares of the final fractions which uses are classified as recycling, OMR and ER are measured and reported in WF-RepTool.

[3] In reality, the comparability of the performances and the RRR of treatment operators is limited by differences in the input WEEE flow

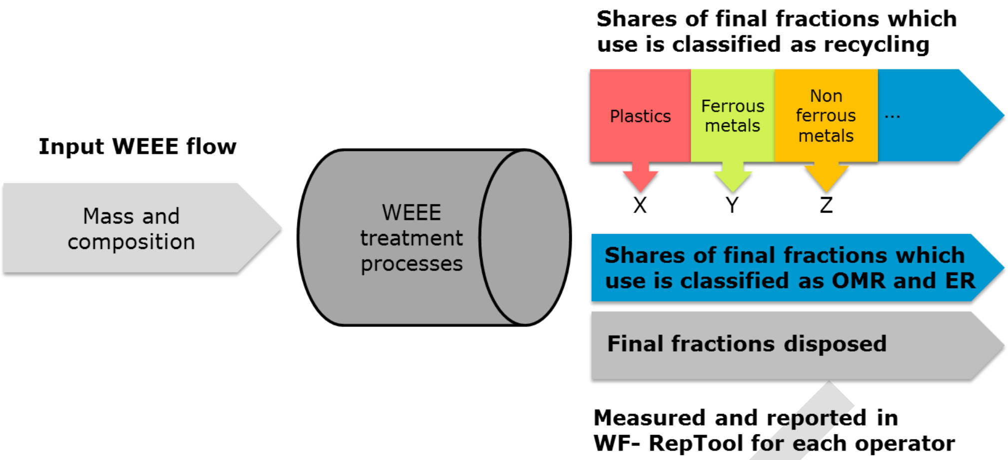

Figure 7: Data required to calculate material-specific recycling and recovery rates (adapted from Eco-systèmes [65])

The method originally discussed with Eco-systèmes [23] and further developed in the frame of this feasibility study consists of following steps:

1. Association of the product with the corresponding WEEE flow, i.e. the mix of appliances, e.g. large household appliances for washing machines and flat panel display appliances for laptops
2. Two steps have to be conducted in parallel to select operators that are representative and that treat the WEEE using the same generic EoL scenario:
    a. Definition of the generic EoL scenario for the considered WEEE input flow (section 2.5) and
    b. Selection of the panel of first step operators achieving the high recycling and recovery rates with their downstream acceptors (section 2.6.2.2)
3. Determination of the total mass of the share of the final fractions classified as recycled or recovered after the treatment chain:
    a. Exploitation of batch report data of the selected first step operators with their downstream acceptors: Determination of the mass of the final fractions produced by the selected operators
    b. Classification of the use of the final fractions in the final technology applied as recycling, energy recovery, other material recovery or disposal (according to the WF-RepTool classification [30])
4. Determination of the mass of the material contained in the WEEE input flow based on composition data collected using e.g. the methodology developed by Eco-systèmes to conduct sampling and analysis campaigns [67]
5. Calculation of the material- and operator-specific RRR by dividing the mass of the share of the final fractions classified as recycled or recovered after the treatment chain by the mass of the corresponding material contained in the WEEE input flow
6. Combination of the data into one or a range of calculated material-specific recycling and recovery rate(s) per material by combining[4] the data of the

[4] An aspect discussed with Eco-systèmes is that the recycling and recovery rates by operators should not be weighted according to their market share [65] as for the calculation of national recycling rates. It is inappropriate for the calculation of the

selected operators[5], under consideration of year N and year N-1 rates for sufficient temporal representativeness (section 2.8.1.3).

7. Association between the share of the final fractions which use is classified as recycled and recovered after the treatment chain and the "materials" of the bill of materials of the product, in case a different granularity is used (e.g.: "ferrous metals" in the BOM is classified as the recycled fractions steel and iron cast)
8. Calculation of the recyclability and recoverability rates of the product based on the BOM

2.8 Available information on data representativeness, validity, and uncertainties

2.8.1 Available information on representativeness

The representativeness of the RRR is defined in terms of:

- Product-related representativeness
- Representativeness related to the treatment technologies
- Temporal representativeness considering changes in the use of treatment technologies
- Geographical representativeness

2.8.1.1 Product-related representativeness

In technical and economically sound operational conditions, first step operators do not treat a given product (e.g. laptop or washing machine) in a specific batch of this product type, but mixed with other products in WEEE collection and treatment flows like 'flat panel display appliances' or 'large household appliances non cold' [65]. The calculation of the material-specific RRR based on a batch containing, instead of the product mixes in the existing conditions of collection and treatment, only the considered type of product would involve:

- lack of representativeness, because (1) in real-life treatment processes do not treat this input mix, and the input characteristics influence the performance of the processes in terms of quantity and quality of output fractions (and, therefore, the RRR) and (2) treatment processes cannot be optimized simultaneously for each product-type (economic and technical conflicts)
- lack of repeatability to build a complete database for many products
- lack of availability of the necessary input amount of individual product for a representative batch
- high costs due to the efforts required to collect, sort and store the necessary input amount of an individual product to run a representative batch

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recyclability and recoverability rates in the context of eco-design policies, because the market shares of the operators are variable and influenced by factors that are not crucial for recyclability, like competition on the WEEE treatment market, organizational decisions and capacities.

[5] a critical analysis of the discrepancies of the recycling and recovery rates of the three operators can result into the exclusion of outliers if justified by a detailed analysis of the operator report

- costs to run numerous treatment batches (treatment)

Therefore, we consider that the material-specific RRR should be calculated for mixes of products treated together in the WEEE collection and treatment flows. These WEEE flows may vary according to the EU countries and the WEEE collection schemes, because some of them collect and treat some specific products separately. Depending on the source of the data, the RRR should be calculated on the basis of the existing conditions of collection and treatment, and therefore be representative for the WEEE flow (mix of appliances) used for the calculation [63]. The calculated material-specific RRR are assumed to be representative for all materials contained in the WEEE flow, irrespective of the type of product in which the material was embedded.

2.8.1.2 Representativeness related to the treatment technologies

Operators complying with the generic scheme of the EoL scenario can achieve different RRR, depending e.g. on:

- managerial and organisational decisions,
- the treatment technologies they use,
- the operator know-how to run these technologies properly,
- their ability to find economically viable downstream processes for the fractions

The recommendation to use data of several first step operators achieving, with their downstream acceptors, the highest overall RRR to calculate the material-specific RRR aims at increasing the representativeness of the rates, because the data basis is broader and less dependent on the decisions taken by a single operator.

The representativeness of the rates calculated for the uses of PCB in integrated smelters is assumed to be very high for the smelters that signed the EERA/Eurometaux standard, because the technology differences lead to significant variation of the recycling rates only for some metals with a low mass share in the PCB. The representativeness of the calculated RRR for smelters that do not comply with the EERA/Eurometaux standard (e.g. outside Europe) is unknown. The operators of interim technologies that send output fractions to these smelters have to gather these data to determine and report their RRR.

2.8.1.3 Temporal representativeness

Due to variation of the WEEE composition, of the operators active on the recycling market, of changes of the used treatment technologies and of other factors, the RRR are varying in time. However, the RRR should be influenced as little as possible by short-term fluctuations that do not reflect fundamental changes of the recyclability and recoverability of the products. Eco-systèmes [65] compared three methods to deal with temporal variability (Figure 8).

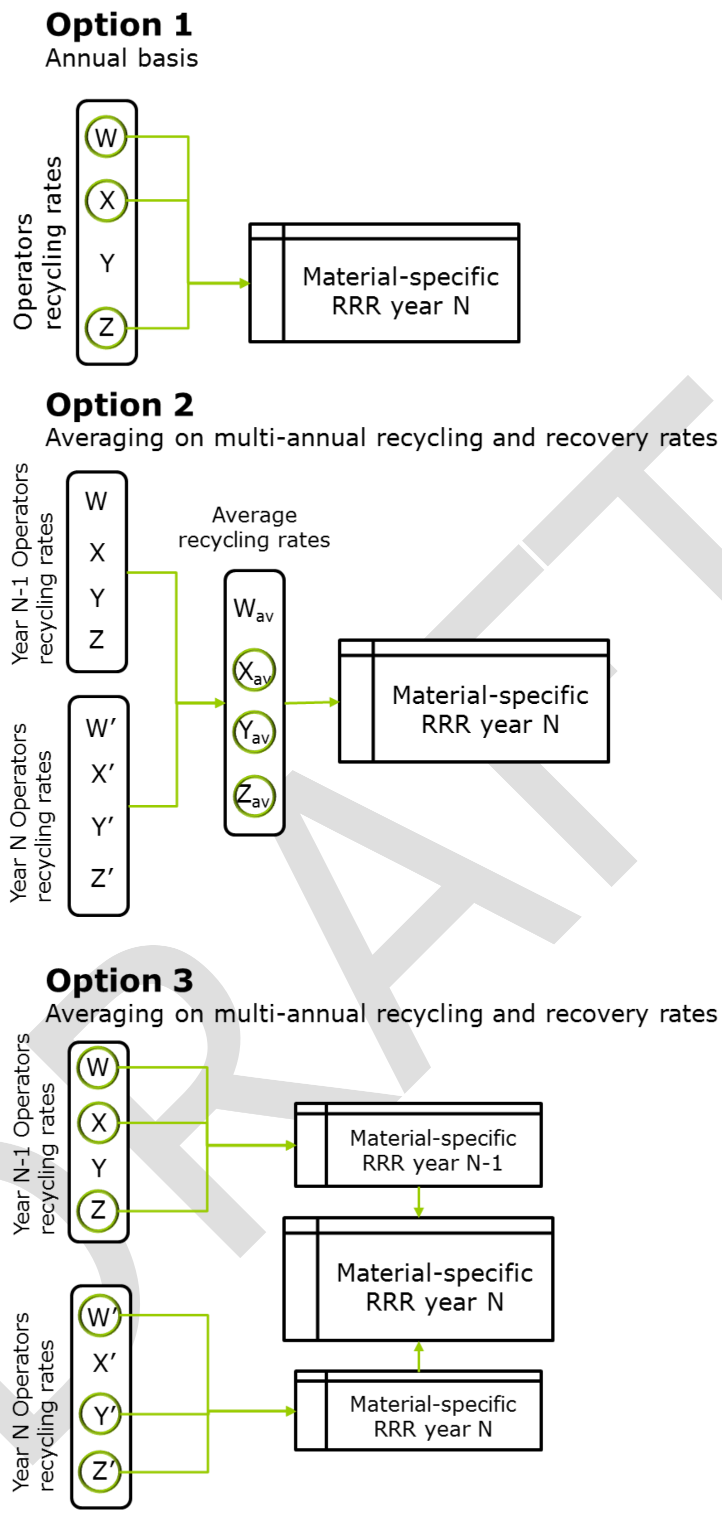

Figure 8: Methods to identify/select representative data sources in a "best available technologies" approach [65]

The outcomes of the comparison were [65]:

- In option 1, the material-specific RRR are calculated based on the recycling and recovery rates reported for one single year. This approach leads to a strong variability of the RRR for some materials, which is not consistent with real evolutions.

- In option 2, multi-annual data on recycling and recovery rates are produced for each operator. Option 2 requires to freeze for several years the selection of operators and ensure the availability of data on several consecutive years for each operator.
- RRR for each year are separately calculated in option 3, under consideration of several operators. The final material-specific RRR are calculated by calculating the average rates of several years. This approach leads to a lower variability than options 3.1 and 3.2 and is preferred.

2.8.1.4 Geographical representativeness

According to Kolba [68], the geographical location of a treatment facility is not a key factor influencing the used treatment technologies. Geographical differences influencing the RRR are more a) given by the composition of the WEEE to be treated (mix and age of appliances) and b) related to the economic and legal framework of the local recycling market. For example, the use of energy recovery as a final process can be affected not only by technical aspects like the composition of the final fractions, but also by available local capacities and economic conditions (costs of incineration compared to landfilling) [69].

To investigate properly the geographical representativeness, harmonized data from more countries would be needed. However, we assume that the data on RRR generated by selecting first step operators achieving comparatively high recycling and recovery rates out of a pool of operators complying with the requirements of the WEEELABEX and EN 50625-1 standards can be considered as representative for Europe.

2.8.2 Available information on validity

The quality of the data on RRR depends on the collection methods used, for which five options are presented by Figure 9 [65]. The highest data validity and reliability is obtained by conducting measurements through a batch analysis under the control of auditors coming from the take-back system and/or accredited by WEEELABEX. Batch analysis without external control may provide data with a lower validity, due to the lack of control of the measurement methods. The validity of declarative data (declarations of the operators based on technical understanding of the processes), empirical data (observations) and estimates is rather low due to the lack of standardization and reproducibility of the measurement. This is valid for each step of the process chain, from the first step operator to the operators of the final technologies.

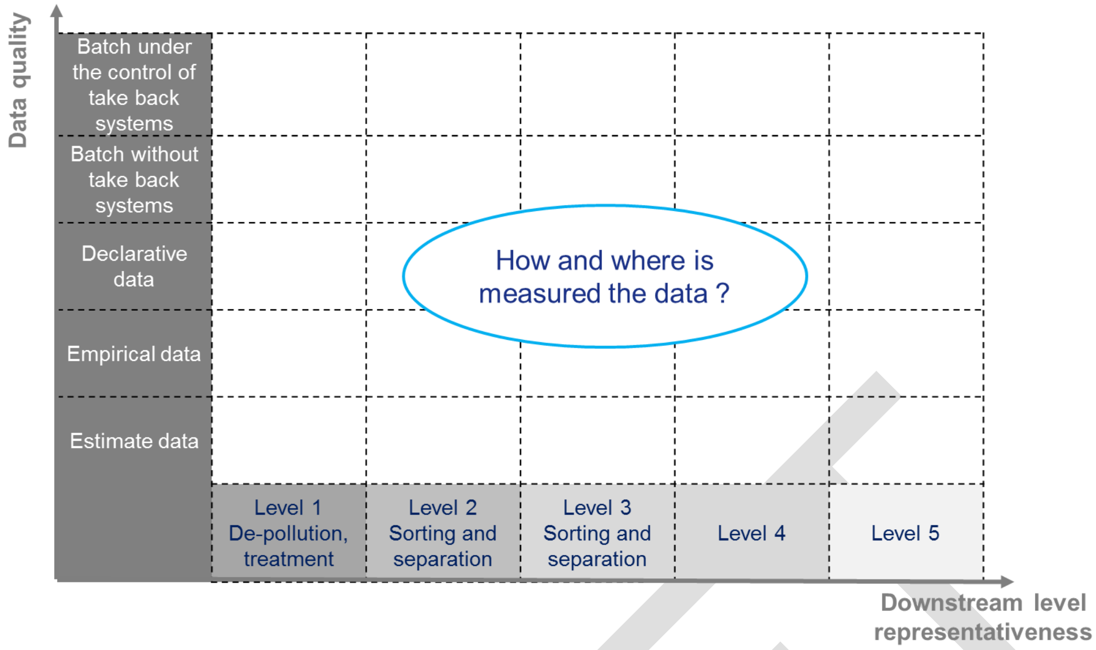

Figure 9: Data quality and representativeness related to the downstream treatment technologies [65]

The use of data with a high validity is particularly essential for treatment operations having a strong influence on the final end-of-life destination of the fractions: for instance, first treatment and sorting operations on the input WEEE flow, sorting intermediary operations on complex output fractions (e.g.: mix of non-ferrous metals and plastics). For standardised final operations on homogeneous/pure fractions, the use of declared or estimated data may have a lower effect on the results [63].

In general, the method of using data from long-term and standardised measurements for the calculation of the material-specific RRR leads to a higher validity than the use of theoretical estimates and one-time experimental trials. Table 8 lists the parameters necessary to calculate the material-specific RRR, the methods used to measure them and the factors possibly decreasing their validity.

Table 8: Validity analysis of the parameters used to calculate the material-specific RRR according to the method described in section 2.7

Parameter	Method	Factors possibly decreasing the validity
Selection of the operators	The method to determine how many and on which criteria operators should be selected is to be defined	Low number of selected operators decreases the reliability of the data and possibilities to conduct statistical analyses Selecting all or most of the operators reflects state-of-the-art treatment technologies, not BAT

Parameter	Method	Factors possibly decreasing the validity
Determination of the share of the final fractions classified as recycled or recovered	Yearly batch analyses	Low granularity of the available data Variability of the input composition: representativeness of the input of the batch analysis Variability of the performance of the manual and mechanical processes: representativeness of the treatment
Mass of this material contained in the input of the WEEE flow	Periodical input analysis campaigns	Average input composition does not necessarily fit the composition of the input of the batch analysis Variability of the WEEE flows
Combination of the data into one or a range of reference value(s) on material-specific recycling and recovery rates	Critical analysis of the discrepancies of the operator-specific RRR – exclusion of outliers justified by a technical analysis of the operator report	Large discrepancies cannot be explained, difficulties to combine the data into one or a range of reference value(s)
Bill of materials of the product associating the materials with the "end-of-waste fractions" recycled and recovered by the treatment chain	Analysis of the product	Variability of the material composition of a product: representativeness of the BOM Lack of consideration of the design parameters influencing the recyclability of the product beyond the BOM

The main limitation of the validity of the calculated RRR is the fact that the mass and composition of the produced final fractions is measured during each batch analysis at the operator, while the input is analyzed on an average basis, at national level for instance, and not for each batch (to keep the costs of the batch analysis reasonable and for practical feasibility reasons). The validity is then limited by discrepancies between the composition of the real input to the batch analysis and the average composition of the WEEE flow at national level.

2.8.3 Available information on uncertainties

All datasets needed for the calculation of the material-specific RRR as defined in Table 3 on page 16 are subject to uncertainties. This applies for example to

- the identification and description of the relevant end-of-life scenario(s) for the WEEE input flow,
- the data on the recycling and recovery rates achieved by the interim and final technologies used in the end-of-life scenario(s),
- the data on the composition of input WEEE flows,

- the average material composition of the products for which the recyclability and recoverability rates are calculated.

In general, the complexity and the variability of all parameters playing a role in WEEE treatment make data collection very challenging. The data collection process of all datasets needs to be documented (like in the ecoinvent database [70]) and become a part of the metadata associated with the reference values (section 5.4.1).

The calculation of RRR is a simple descriptive material flow analysis. An overview of methods available to deal with uncertainties in material flow analyses was published by Laner et al. [71]. Usually, no detailed information on the uncertainties associated with the parameters used to calculate the material-specific RRR (precise magnitude, distribution) is available. Therefore, the available information does not allow feeding a complex model with data and only simple methods applicable on descriptive material flow analyses come into consideration for the estimation. These methods are summarized in Table 9.

Table 9: Methods available to deal with uncertainties in descriptive material flow analyses (from Laner et al. [71])

Approach	**Data uncertainty characterization and mathematical treatment**	**Method to combine the uncertainties of the data sets**
Confidence ratings	Assignments of confidence levels for the data. No mathematical treatment possible.	Ratings (qualitative or scores)
Asymmetric intervals	Data source- and specificity-based concept to derive asymmetric intervals defined by multiplication and division with an uncertainty factor	Interval arithmetic (addition of lower and upper bounds)
Symmetric intervals	Intervals defined by lower and upper interval values contain the true value with a certain level of confidence	Interval arithmetic (addition of lower and upper bounds)
STAN software	Uncertain data are specified as the mean and standard deviation of a normal distribution	Gaussian error propagation

The method ‘confidence ratings’ is not recommended for the database, because it does not enable combining the uncertainties of different parameters. The method used in the ‘STAN software’ requires assuming a normal distribution. This assumption cannot be verified for the uncertainties on the reference values that will feed the database, so that the method is not recommended. Both methods ‘asymmetric’ and ‘symmetric’ intervals require no assumptions on the distribution and are simple to apply. Finally, the method ‘asymmetric interval’ is prefered, because it “enables a transparent categorization of uncertainty ranges for data from different sources” [71].

Concretely, all parameters used to calculate the recyclability and recoverability rate should be considered to estimate an uncertainty factor through the assessment of the data validity. For example, if a factor of 1.1 is defined as the uncertainty factor of a parameter with an estimated value y, it means that the parameter is assumed to be in the interval:

$$[\ y / 1.1\ ;\ y \times 1.1\ ]$$

Regarding the error propagation, the lower and upper bounds of the intervals in which the recyclability and recoverability rates are assumed to be are calculated based the lower and upper bounds of the intervals of all parameters used in the calculation of the rates.

So far, the methods MEErP and REAPRO do not consider uncertainties. In the study of the CODDE [19], the degree of precision of the calculated recyclability and recoverability rates is assumed to be 5%, which corresponds to an uncertainty factor of 1.05.

An option to estimate the overall uncertainty of the recyclability and recoverability rates would be to estimate the uncertainties of each parameter listed in Table 8. The data availability does not allow this estimation. A more feasible option is to quantify the variability of the recyclability and recoverability rates based on the variability of the data from the different selected operators with indicators like the standard deviation.

2.9 Structure of the database containing the reference values

Figure 10 shows a draft of the database structure including the tables:

- **Product Type** according to the classification of EEE of Wang et al.[32] (section 2.4.2.1). One or several **Product Types** can be assigned to a **WEEE flow** (treatment category).
- One or several **Products**[6] which a characterized through the attributes *Weight* and a *product name* are related to a **Product Type**
- The specific **Product** consists of several **Materials** (section 2.4.2.2 and Table 5) having the attributes *Weight* and *Weight ratio* (required to estimate the recyclability and recoverability rates) and a second attribute Q*uality* defining for example the "purity" of the material or the grade of the PCB. The *Material Type* can be chosen from the table **Material Type**. The auxiliary table **ProdMat** is required to define a m:n relationship between **Product** and **Material,** which means that one product can consist of several materials and one material can be used for different products. This structure allows to save RRRs for a WEEE flow, a product type or a specific product.
- The table **Recycling/Recovery Rate** indicates which average *RRR* are achieved with the selected **End-of-life scenario** for a specific **Material**. The *standard deviation*, *minimum* and *maximum* of the RRR can also be added. Here again the auxiliary table **MatRRR** defines the m:n relation between **Material** and material specific **RRR**, i.e. one material can have different RRRs (depending on the end-of-life scenario) and one specific RRR can apply for several materials. In the field *Description of Output* more information on the composition, type and quality of the share of final fraction recovered or recycled can be given.
- The table **End-of-life scenario** defines which *end-of-life scenario* is used.
- The table **Metadata** enables the collection of metadata for each **Product**, **RRR**, **Material**, and **End-of-life scenario**

This database structure provides the required data sets to estimate the RRR for (typical or average) products. The actual multiplications of weight fractions of the

[6] A product can be a specific brand model or just an example representing a typical or average product (e.g. data coming from the disassembly of several products)

materials times the calculated material-specific RRRs in order to calculate the products recyclability and recoverability can be implemented through a data query.

The proposed database structure does currently not allow entering qualitative information on the shares of the final fractions classified as recycled or recovered (e.g. naming the produced secondary raw material). The benefits and limitations related to the collection of this information is discussed in section 5.2.4. It would be technically feasible to implement this additional function into the database by adding into the table Recycling/Recovery Rate a field named e.g. "output material" and linked to the table Material Type. This table would have to be expanded to consider the variety of recyclates and other final fractions.

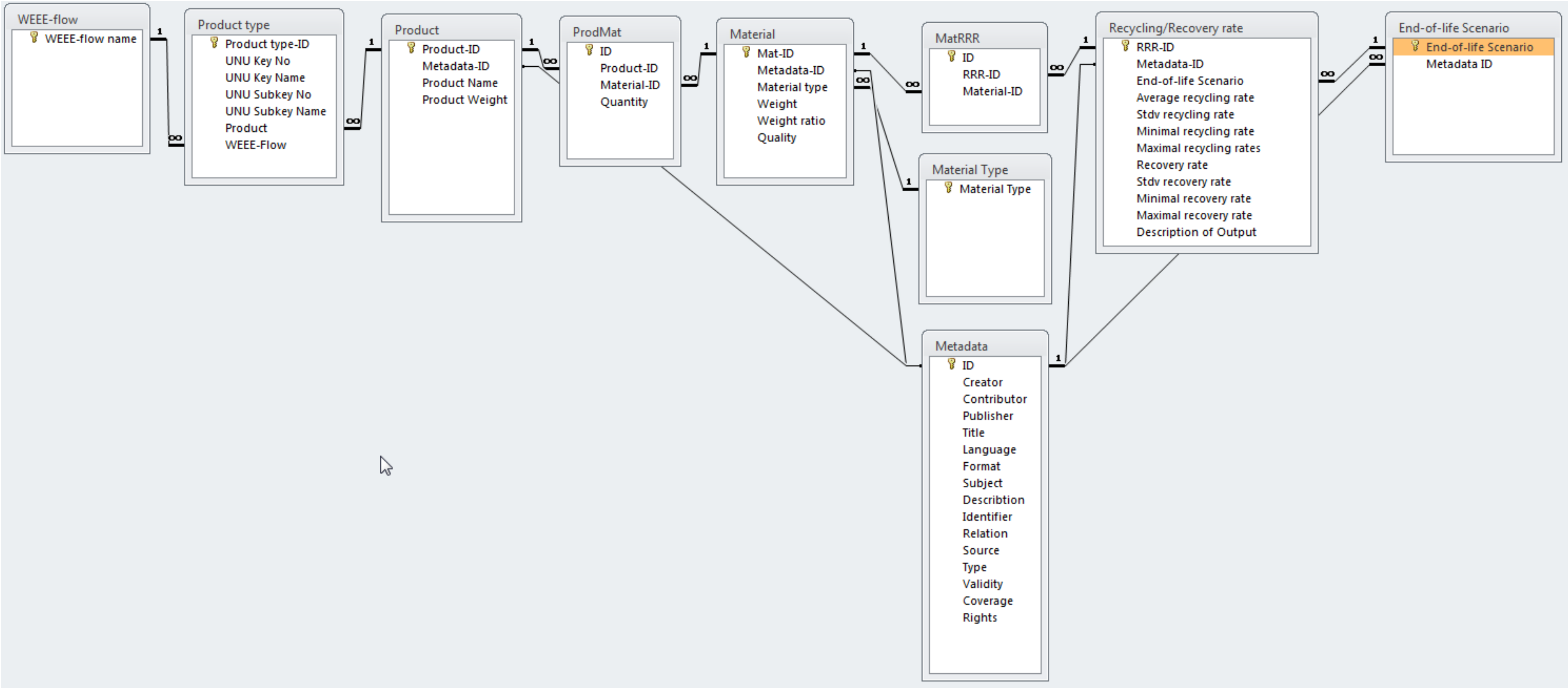

Figure 10: Draft database structure

3 Testing of the methodology

3.1 Selection of the case studies

3.1.1 Identification of relevant product groups

This section aims at presenting the process aiming at identifying two relevant product groups of EEE, for which the foreseen reference values would be particularly useful. The selected product groups are:

1. **Laptops**, due to the high and relatively stable sales volumes, the relevance for recycling in terms of resources and the data availability. The product groups ultrabooks and tablets, which have properties close to the laptops, were also be considered,
2. **Washing machines**, which makes out the largest part of the large household appliances [39]. They are relevant for ecodesign requirements and currently addressed by the revision of the Energy Label regulation 1061/2010 and of the Ecodesign Regulation 1015/2010 on household washing machines. The applicability of the data to related product groups like dishwashers and tumble driers was also investigated.

3.1.2 Identification of relevant materials and components

An exhaustive list of materials and components contained in our case studies laptops and washing machines was compiled through the bill of materials (section 3.2.2 and Table 5). Derived from this list of materials and components, a sample of relevant materials or components contained in the two selected product groups was built. The final sample was supposed to include at least one metal, one polymer, one precious metal component and one complex component. The availability of data from the reports on RRR, the mass of the materials and components and their relevance from an environmental and economic point of view were considered to build the sample. The sample also includes materials or components containing CRM as defined by the European Commission [61]: the focus was set on cobalt from batteries and palladium from populated PCB, for which recycling is technically and economically feasible (Table 7). Table 10 lists the sample of materials contained in laptops and washing machines that were selected in order to test the methodology.

Table 10: List of materials / components / CRM from laptops considered for the sample

Material or component	Product group
Thermoplastics	Laptop + Washing machine
Non-ferrous metals: aluminium and copper	Laptop + Washing machine
Ferrous-metals	Laptop + Washing machine
Printed circuit boards (palladium, precious metals)	Laptop + Washing machine
Drives	Laptop
Hard Disk	Laptop
LCD Panel	Laptop
Lithium-Ion batteries (cobalt)	Laptop
Mineral fraction: glass, concrete and other mineral materials	Washing machine

3.2 Data collection for calculating the material-specific RRR

Following the method proposed in section 2.7, the calculation of the recyclability / recoverability rates of products includes following steps:

1. Definition of the EoL scenario
2. Bill of material of the product
3. Data extraction from the reporting of the RRR
4. Calculation of the recyclability / recoverability rates

3.2.1 Definition of the EoL scenarios

As described in section 2.5, the generic end-of-life scenario is not too detailed and describes the reference network of economically running treatment processes. The specific treatment technologies used to treat the WEEE (e.g. liberation technologies like shredders or smashers, separation technologies for plastics), as well as the order in which the technologies are used, can vary according to the operators.

The generic scenarios presented in Figure 11 (laptops) and Figure 12 (washing machines) are based on treatment technologies used by the operators of Eco-systèmes and on scenarios described and observed by Renate Gebriel by using the WF-RepTool (Annex 5). To "cover" the different treatment options and sequence of treatment technologies, the generic EoL scenarios are more simple and abstract than a "real" chain of treatment technologies.

Figure 11 shows the generic EoL scenario adopted for laptops. After extraction, usually manually, of the battery and of the display unit, further manual sorting (removal of e.g. circuit boards, hard discs, DVD drives etc.) and/or mechanical liberation (shredding) takes place. After that, further separation and conditioning generates fractions being forwarded to final technologies [72].

The display unit are normally further dismantled into e.g. iron fractions, plastic fraction, LCD panel and circuit board fraction[7]. At present, LCD panels are stored or treated with technologies that are still evolving. Other fractions are sent to further interim and final technologies.

[7] The display unit is usually removed for decontamination, i.e. liquid crystal displays of a surface greater than 100 square centimetres and of removal of the mercury containing CCFL backlighting. As however it is assumed that newer products do just have LED backlighting, the mercury containing fractions are not considered here.

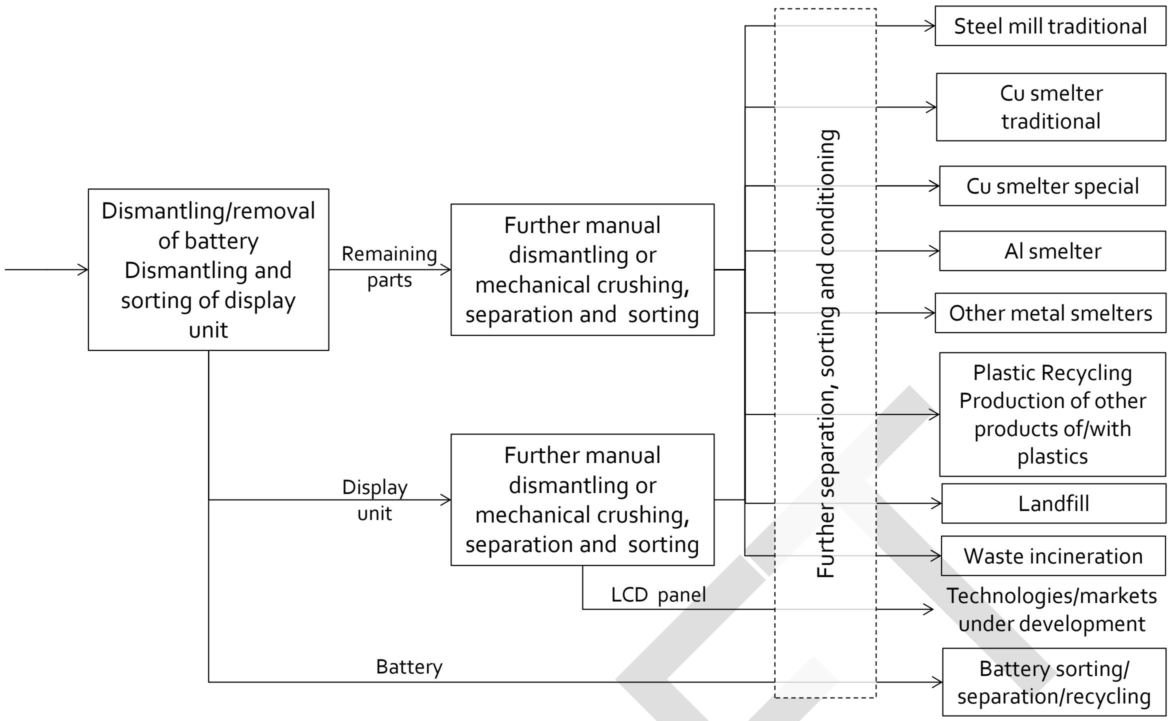

Figure 11: Generic EoL scenario for laptops

Figure 12 shows the generic EoL scenario adopted for washing machines. A first manual dismantling and sorting of complex parts like cables, capacitors and concrete usually takes place, possibly normally followed by mechanical opening (e.g. with an impact crusher) of the washing machine. After this mechanical opening, parts such as external power supply cables, concrete parts, printed circuit boards, motors, and capacitors possibly containing PCB may be sorted manually (hand-picking). PCB containing capacitors are incinerated as hazardous waste. The rest of the washing machines is further crushed in a medium or a large shredder after which fractions are further separated manually or by different automated separation technologies. Those fractions are sent to the material-specific interim or final technologies for further separation to final fractions (e.g. separation of non-ferrous metals or plastics conditioning for plastics fractions) or are directly applied as final fractions in the final technologies (e.g. iron fractions sent to steel mills) [72], [73].

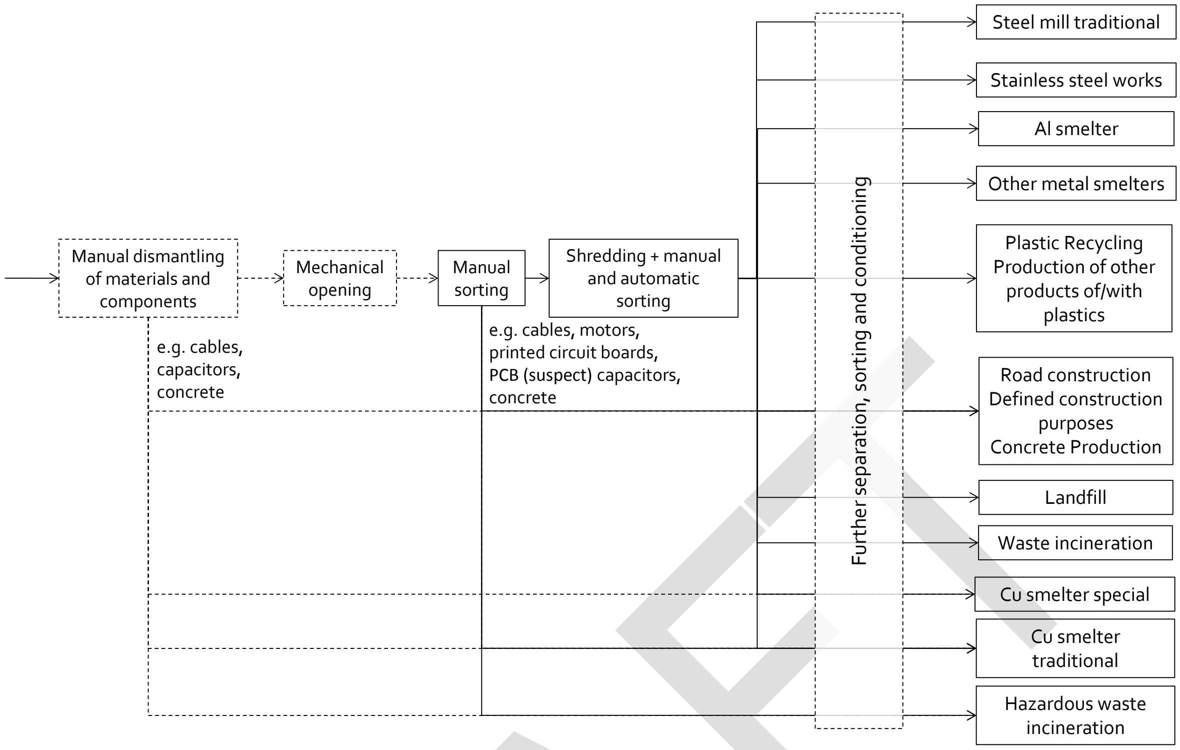

Figure 12: Generic EoL scenario for washing machines

3.2.2 Bill of materials

In this chapter, it is assessed:

- Which information of the material composition of EEE (laptops, washing machines) is available
- How this information can be transferred into a Bill of Material (BoM) suitable to estimate the recyclability and recoverability rates (estimation of effort and experienced challenges), with a special focus on PCB
- Whether Table 5 (Classification of the materials and components used in EEE) has to be complemented by other materials
- How reliable and representative the collected data is

According to BIO Intelligence Service and Fraunhofer IZM [10] a bill of material is a "list of materials/components a product is made of". For the purpose of the recyclability database not just the list, but also the weight of the material/components have to be collected. To calculate the recyclability and recoverability rates, a typical, generic or average composition of a product (e.g. a laptop) is necessary. Possible types of materials are listed in Table 5, which classifies the materials used in EEE and associates them with fractions used in WF-RepTool. Complex parts should be assigned to the materials under consideration of the weight fraction of each embedded material (e.g. breakdown of keyboard to plastics, stainless steel etc.).

Gathering data on the average material composition of electronic products is a challenge, because the manufacturers continuously adapt the use of materials to put attractive products onto the market, to respond to the demand of consumers (product types, functions) and to react to technological innovations. For the purpose of testing the estimation of the recyclability and recoverability rates of washing machines (WM) and laptops a detailed analysis of literature was performed to obtain reliable data on the material composition of selected materials and components in section 3.1.2.

3.2.2.1 BOM for washing machines

Table 11 shows the compositions fo three different washing machines (WM). Ardente & Mathieux [51] estimate the recyclability and recoverability rates for two washing machines: the composition of WM 1 is representative of the medium-price segment and the BoM from WM 2 is representative for the high-price segment. The data are derived from Rüdenauer & Gensch [74] and have been complemented by additional information from manufacturers. According to equipment manufacturers, the BOMs are currently representative for the European recycling situation, although they might not be representative for current products put on the market [51]. A newer BOM of a washing machine (WM 3) was collected for the review of the preparatory studies for the EuP directive LOT 14 "Domestic washing machines and dishwashers" [75] which consists more or less of the same materials apart from small differences in types of plastic resins used.

Table 11: Weight fraction of materials in washing machines [51] [75]

Materials	WM 1			WM 2			WM3	
	mass [g]	Percentage of product mass [%]	Details of the content	mass [g]	Percentage of product mass [%]	Details of the content	mass [g]	Percentage of product mass [%]
Acryl-Butadien-Styrol (ABS)	1.228	1,7%	360g in the frame of the porthole. Other ABS in various components	1.196	1,2%	360g in the frame of the porthole. Other ABS in various components	1.874	2,7%
Aluminium	2.313	3,2%	various components (not defined)	3.608	3,7%	various components (not defined)	2.527	3,6%
Brass	73	0,1%	various components (not defined)	-	-	-	-	-
Cable	781	1,1%	50% (390.5g) of external cables	952	1,0%	50% (476g) external cables	511[#]	0,7%
Chipboard	2.057	2,9%	located at the top of the WM	2.468	2,5%	located at the top of the WM	-	-
Concrete	22.740	31,7%	70% (15.92 kg) located at the bottom of the WM. 30% located internally	-	-	-	20.186	28,8%
Copper	925	1,3%	In the motor	1.027	1,1%	In the motor	1.460	2,1%
Cotton with phenolic binder	525	0,7%	cotton mat for insulation	1.620	1,7%	cotton mat for insulation	-	-
Electronic Components	362	0,5%	Printed circuit board (with capacitor: 10g) intermediate in terms of content of precious metals	1.929	2,0%	Main board (PCB rich: 321g; PP:110g): Secondary board (PCB intermediate:715g; PP frame: 200g; Al heat sink: 200g; Capacitor: 30g); LCD screen 58.5 cm2 (without lamp) with PCB poor (120g) and ABS frame: (233g);	225	0,3%
Ethylen-Propylen-Copolymer (EPDM)	2.220	3,1%	Pipes	2.960	3,0%	Pipes	1.581	2,3%
Glass	1.931	2,7%	Front door	1.476	1,5%	Front door	1.870	2,7%

Materials	WM 1			WM 2			WM3	
	mass [g]	**Percentage of product mass [%]**	**Details of the content**	**mass [g]**	**Percentage of product mass [%]**	**Details of the content**	**mass [g]**	**Percentage of product mass [%]**
Cast iron	1.304	1,8%	various components (not defined)	28.780	29,7%	Cast iron (28kg) used in the counterweight (located at the bottom of the product).	1.916	2,7%
Polyacryl (PA)	17	0,0%	various components (not defined)		0,0%	various components (not defined)		0,0%
Polyethylen (PE)		0,0%		27	0,0%		16	0,02%
Polymethylmethacrylat (PMMA)	3	0,0%		185	0,2%		49	0,1%
Polyoxymethylen (POM)	-	-		26	0,0%		136	0,2%
Polypropylen (PP)	175	0,2%		489	0,5%		8.766*	12,5%
PP 20% mineral filler	421	0,6%		41	0,0%		-	-
PP 40% mineral filler	8.012	11,2%		1.410	1,5%		-	-
Carboran 40%	-	-		775	0,8%		-	-
Polystyrene (PS)	219	0,3%		-	-		-	-
Steel	24.320	33,9%	1.5 kg in the motor. Other steel in various components	44.733	46,1%	2 kg in the motor; (including in the magnets: neodymium 40g; praseodymium 10g; dysprosium 10g; terbium 5g). Other steel in other components.	28.808	41,1%
Other materials	2.118	3,0%	various components (not defined)	3.350	3,5%	various components (not defined)	182**	0,3%
Total product	71.744	100,0%		97.052	100,0%		70.107	100,0%

Copper wire (409 g) and insulation (102 g) of cable tree
* PP (2,155 g) and glass fibre filler (6,611 g)
** Sum of mass of PET (24 g), Talkum (131 g), PA (26g) and PUR (1 g)

A less detailed analysis of the material composition is given by Oguchi et al. [40] in Table 12. The data stem from models from 1996 and 2002.

Table 12: Weight fraction of materials in a washing machine [40]

Equipment type	Number of data	Ferrous material	Aluminium material	Copper cable and material	Plastic	Printed circuit board	Battery
Washing machine	3	51.7 %	2.0 %	3.1 %	35.3 %	1.7 %	

3.2.2.2 BOM of laptops

Attempts to collect, summarise and publish general data on the material composition of laptops were done by several research groups [37]–[40], [76], [77]. Table 12 shows the average composition of laptops as stated in Kasulaitis et al. [74], FEM / IUTA [76] and Oguchi et al. [40].

Table 13: Weight fraction of materials in laptops

Source / **Materials**	**Kasulaitis et al.** [77]	**FEM / IUTA** [76]	**Oguchi et al.** [40]
Ferrous material	10%	11%	19.5 %
Aluminium material	14%	4%	2.4 %
Copper cable and material	2%	0.4%	1.0 %
Plastic	24%	38%	25.8 %
Printed circuit board	14%	16%	13.7 %
Magnesium	4%	-	-
Battery	13%	11%	14.4 %
LCD	18%[1)]	8%[2)]	-
Drives[3)]	-	8%	-
Hard Disk	-	4%	-
Number of data	8	451	10

1) LCD module, probably including backlighting unit (diffuser etc), CCFL tubes and other materials
2) LCD panel without backlighting unit (LED or CCFL tubes)
3) CD-rom-, DVD- and floppy drives

It appears that the listed materials differ in each source. Whereas all sources consider the materials Fe, Al, Cu, plastics, PCBs and batteries, some complex parts such as drives or LCDs are listed separately by FEM / IUTA [76]. Magnesium is listed by the newest source [77] because it is found in laptops of newer generation as lightweight constructive frame. Kasulaitis et al. [77] disassembled 11 laptops in order to detect material productivity (performance/weight) trends over time. The eight models stem from 1999 until 2007 (one model each year) with a screen size of 14.1‟. The 10 datasets from [40] stem from models from 1987 until 2008, partially taken from literature and also measured by the author. For the study of FEM / IUTA [76], trained personal in a certified recycler disassembled 451 laptops manually according to a disassembly manual. It is also not clear how old the laptops were. It can be assumed that all disassembled laptops still have CCFL backlighting, a bill of material for a laptop with LED backlighting could not be found in the literature.

Depending on the processes employed in the end of life scenario (e.g. manual separation of hard disks or screen unit for separate treatment) and the outputs of the first interim technology, complex parts such as the display unit, the drives and the hard disks have to be further broken down into different materials.

Ueberschaar & Rotter [78] assessed the composition of hard disks. They disassembled over 40 hard disk drives from desktop PCs (Table 14) and 6 HDDs from laptops. The laptop HDDs have an average weight share of 3.6 % at the laptops and a slightly higher share for the magnets (5.8 ± 0.7 %) and the PCBs (13.1 ± 0.2 %). Unfortunately, the full BoM of Laptop HDDs is not available because the primary interest of the study [78] were the magnets so that the Laptop HDDs were not fully dismantled.

Table 14: Weight fraction of materials in hard disks in desktop PCs [78]

Materials	**Weight fraction**
Ferrous metals	20 ± 9 %;
Non-ferrous metals	67 ± 13 %
Printed circuit boards	6 ± 2 %.
NdFeB magnets	3 ± 1.5 %
Plastics	0.8 ± 0.7 %;
Rest	5.5 ± 1.7 %.

Normally, the upper part of a laptop (display unit) including the LCD panel, the CCFL backlighting and the plastic housing is separated from the "body" of the laptop for selective treatment because of the mercury containing CCFL backlighting, as shown by the EoL scenario (Figure 11). Figure 13 shows the different parts of a laptop with LED backlighting.

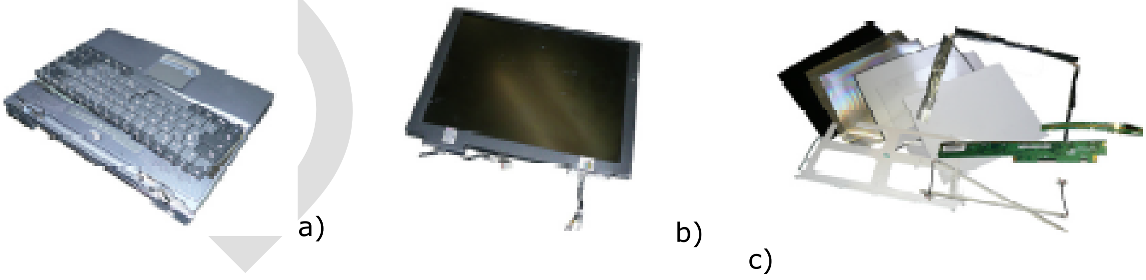

Figure 13: Body (a), display unit (b) and disassembled display unit (c) (LCD panel, plastic frame, steel frame, light spreader/diffusion foils, high grade printed circuit boards (including LED backlighting)) of a Laptop [79]

The average weight fraction of this upper display unit coming from a disassembly of 6 laptops is 33 % (Std dev. 3 %) [80] and another disassembly of 5 laptops resulted in an average weight fraction of 38 % (Std dev. 8 %) for the upper screen part and an average weight fraction of the battery of 17 % (Std dev. 5 %) [81]. The disassembly of the display unit resulted in the bill of materials shown in Table 15 [80]. The weight fraction of the LCD panel in the laptop is 9 %, similar to the number stated by FEM / IUTA [76], which suggests that the LCD fraction stated by Kasulaitis et al. [77] still contains the backlighting unit including diffusion foils/light spreader and CCFL tubes.

Table 15: Weight fractions of materials in the display unit of laptops (6 datasets) [80]

Materials	Average [%]	Std dev [%]
LCD panel	28,0	1,50
PCB	1,95	0,60
CCFL Tube	0,23	0,18
Cu and Cu alloys	0,13	0,33
Mg and Mg alloys	0,00	0,00
Steel and steel alloys	3,91	4,15
Al and Al alloys	5,25	0,87
Black plastic	33,65	3,89
white plastic	2,03	0,95
Magnet alloys	0,62	1,52
Plastic foils	20,20	3,22
Al/Cu/Plastic	0,00	0,00
Fe/Cu/Plastic	0,36	0,89
others	1,10	1,50
Fe/Al	0,87	2,13
plastic copper	0,08	0,19
Wire	1,49	0,70
Sum	99,88	

3.2.2.3 Composition of the printed circuit boards

Table 16 shows data for the material composition of printed circuit boards from several sources. Oguchi et al. [40] list the metal content of printed circuit boards (PCBs) of washing machines (average of several samples) and notebook PCs (average of 10 products from 1987 until 2008). Huisman et al. [39] publish average printed circuit board compositions per treatment category. Ardente & Mathieux [73] list the composition of different PCBs classified into "poor", "intermediate", and "rich" in terms of content of precious metals[8]. The content of precious metals in the PCB was estimated by ADEME [82] and UNEP [83], the content of other materials by Mohite [84]. Aurubis provided estimations based on samples [85].

[8] This classification is partially done by pre-treatment companies and smelters in order to indicate the value of the different types of dismantled PCBs

Table 16: Weight fractions of elements in printed circuit boards of end-of-life EEE (mg/kg) [39], [40], [73], [85]

Source	Oguchi et al. [40]		Huisman et al. [39]		Ardente & Mathieux [73]			Nolte [85]	
	Equipment type		**Treatment category**		**Type of PCB**				
	Washing machine [mg/kg]	**Notebook PC [mg/kg]**	**Mix of Large household equipment [mg/kg]**	**Mix of IT except CRT-monitors [mg/kg]**	**poor [mg/kg]**	**inter-mediate [mg/kg]**	**rich [mg/kg]**	**PCB mix [mg/kg]**	**Comments**
Al	1000	18,000	77,000	20,000	22,100	22,100	22,100	20,000-100,000	30-50 % as metal, as oxide in ceramics, possibly as flame retardant in PCB base material
Ag	51	1,100	160	5,700	520	700	1,000	100-1000	
As	N/A	N/A	N/A	27	10	10	10	N/A	
Au	17	630	40	1,300	70	100	250	20-200	
Ba	65	5,600	N/A	N/A	3,200	3,200	3,200	2,000	additive compound in plastics
Be	N/A	N/A	N/A	88	1	1	1	N/A	
Bi	51	120	N/A	200	N/A	N/A	N/A	N/A	
Cd	N/A	N/A	N/A	1	0.14	0.14	0.14	<1000	
Cl	N/A	N/A	N/A	1,000	N/A	N/A	N/A	2,000-4,000	in plastic compounds?
Co	16	80	N/A	N/A	400	400	400	1,000-3,000	as metal in compounds
Cr	N/A	N/A	0	25,000	50	50	50	2,000-3,000	as metal coating in compounds against corrosion and diffusion
Cu	70,000	190,000	130,000	100,000	196,000	195,900	195,800	100,000-250,000	as metal
Fe	95,000	37,000	99,000	80,000	35,700	35,700	35,700	20,000-40,000	as metal
Ga	–	10	N/A	N/A	N/A	N/A	N/A	N/A	
Hg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	<10	

Source	Oguchi et al. [40]		Huisman et al. [39]		Ardente & Mathieux [73]			Nolte [85]	
	Equipment type		**Treatment category**		**Type of PCB**				
	Washing machine [mg/kg]	**Notebook PC** [mg/kg]	**Mix of Large household equipment** [mg/kg]	**Mix of IT except CRT-monitors** [mg/kg]	**poor** [mg/kg]	**inter-mediate** [mg/kg]	**rich** [mg/kg]	**PCB mix** [mg/kg]	**Comments**
Ni	N/A	N/A	1,000	35,000	4,300	4,300	4,300	2,000-10,000	as metal
Mn	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5,000-10,000	part of Cu alloys in resistors
Pb	2,200	9,800	15,000	14,000	26,600	26,600	26,600	10,000-30,000	as metal
Pd	–	200	20	470	10	20	115	5-50	
Pt	N/A	N/A	N/A	N/A	0	0	40	N/A	
S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1,000-3,000	chemical combination with Ba
Sn	9,100	16,000	24,000	21,000	N/A	N/A	N/A	10,000-20,000	as metal
Sr	9	380	N/A	N/A	N/A	N/A	N/A	N/A	
Ta	–	5,800	N/A	N/A	N/A	N/A	N/A	N/A	
Zn	2,400	16,000	32,000	14,000	3,200	3,200	3,200	5,000-20,000	as metal
Glass	**N/A**	**N/A**	**N/A**	**38,000**	**309,000**	**309,000**	**308,800**	**140,000-360,000**	
Si	N/A	N/A	N/A	-	-	-	-	100,000-250,000	mainly as SiO2 (about 50 % of e-glass fibre in PCB base material)
B	N/A	N/A	N/A	-	-	-	-	10,000-30,000	as B2O3 in e-glass
K	N/A	N/A	N/A	-	-	-	-	similiar to Na	as oxide in e-glass
Ca	N/A	N/A	N/A	-	-	-	-	20,000-70,000	as oxide in e-glass
Mg	N/A	N/A	N/A	-	-	-	-	2,000-5,000	as oxide in e-glass, as metal in alloys

Source	Oguchi et al. [40]		Huisman et al. [39]		Ardente & Mathieux [73]			Nolte [85]	
	Equipment type		**Treatment category**		**Type of PCB**				
	Washing machine [mg/kg]	**Notebook PC [mg/kg]**	**Mix of Large household equipment [mg/kg]**	**Mix of IT except CRT-monitors [mg/kg]**	**poor [mg/kg]**	**inter-mediate [mg/kg]**	**rich [mg/kg]**	**PCB mix [mg/kg]**	**Comments**
Na	N/A	N/A	N/A	-	-	-	-	2,000	as oxide in e-glass
Plastics general	-	-	440,000	530,000	-	-	-	-	
Epoxy resin	**N/A**	**N/A**	**N/A**	**1,000**	**198,100**	**198,000**	**197,900**	**-**	
C	N/A	N/A	N/A	-	-	-	-	250,00-350,000	Mainly as epoxy resin from PCB base material, but also as part of components/connectors (probably PE, PP) and flame retardent
Ceramic	N/A	N/A	N/A	N/A	108,400	108,400	108,300	N/A	
Flame retardent (TBBP-A)	**N/A**	**N/A**	**140,000**	**N/A**	**91,000**	**91,000**	**90,900**	**N/A**	
Br	N/A	N/A	N/A	38,000	N/A	N/A	N/A	20,000-50,000	as oxide in flame retardant
Sb	N/A	N/A	1,000	3,000	1,000	1,000	1,000	1,000-5,000	as oxide in flame retardant
P	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	as oxide in flame retardant

The sources usually provide just the content of some elements. The most comprehensive data comes from Nolte [85]. The data are not product specific but refer to an average mix of PCBs going into a smelter. Apart from Cr, the data [73] fit to the ranges/orders of magnitude given by Nolte [85]. Listed are sometimes elements and sometimes compounds (such as epoxy, plastics, ceramics). Even if single elements are listed, they are often present as alloys or compounds. Huisman et al. [39] for example list "plastics general" probably also including the PCB base materials consisting of epoxy and glass fibre, both listed separately by Ardente & Mathieux [73]. Nolte [85] breaks the glass fibre down to its single chemical elements such as Si, Ca, Mg, B, Na and K, all in oxidized form [86].

Due to the weight fraction of PCBs in laptops of 14 to 16 %, their recyclability has a strong influence on the overall mass-based recyclability rate for laptops. For washing machines, the impact is negligible for the final number. However, it is crucial to estimate the recyclability of elements (element groups) contained in PCBs because of the relevance of precious and trace metals from an economic, environmental and/or criticality perspective. To summarise, it is important to use a representative BoM for the device because the PCB composition strongly influences its recyclability rate.

3.2.2.4 Adaption of the list of materials

In addition to the materials listed in Table 5, the BoM for washing machines [51] lists further types of plastics (Ethylene-Propylene-Copolymer (EPDM), Polymethylmethacrylate (PMMA), Polyoxymethylene (POM)), Cotton with phenolic binder, Brass and Chipboard which are not specified as output fractions in WF-RepTool.

It would be possible to specify the type of plastic using "other plastic parts". "Chipboard" can be subordinated to "wood". Cotton or other types of fabrics do not appear in the WF-RepTool list of fractions as they are normally not extra separated during treatment. Fabrics can be classified as "other material", which can be related to "other components/fractions from dismantling or sorting" or "residues from separation" in WF-RepTool. This "other material" can be specified in the attribute "description" in the metadata table of the database or in case of WF-RepTool in the remark field "internal name".

The second option is to expand the list of materials and/or combine different materials in one group for example ferrous or non-ferrous materials. We added EPDM, PMMA, non-ferrous metals and brass to the list of materials – however, we do not pretend that the list covers all materials from all products.

Table 17: Classification of the materials/components used in EEE (updated)

Material and components	**Correspondance to WF-RepTool output fractions**	
	code	**Name of the fraction**
Iron	16 02 16 / 01	iron-rich' fraction from dismantling
	16 02 16 / 02	iron-metals 'pure' from dismantling
	19 12 02 / 01	iron fractions for further separation or for 'final processes'
Stainless steel	16 02 16 / 08	stainless steel 'pure' from dismantling
	19 12 02 / 02	stainless steel fractions for further separation or for 'final processes'
Non-ferrous metals	19 12 03 / 02-2	Mix of non-ferrous metals pure

Material and components	Correspondance to WF-RepTool output fractions	
	code	Name of the fraction
Aluminium[9]	16 02 16 / 03	aluminium-rich' fraction from
	16 02 16 / 04	dismantling aluminium-metals 'pure' from dismantling
	19 12 03 / 03	aluminium fractions for further separation or for 'final processes'
Brass	N/A	N/A
Copper[1]	16 02 16 / 05	copper-rich' fraction from dismantling
	16 02 16 / 06	copper-metals 'pure' from dismantling
	19 12 03 / 05	copper fractions after further separation for 'final processes'
Zinc[1]	19 12 03 / 07-3	zinc 'pure'
Rare earths	19 12 11* / 04-9	rare earths containing fractions
Mercury-containing parts	16 02 15* / 01-2 19 12 11* / 05	mercury containing ‘parts’ dismantled mercury containing fractions
High-grade printed circuit boards	16 02 15* / 02-1	printed circuit boards from dismantling – high quality
Medium-grade printed circuit boards	16 02 15* / 02-5	printed circuit boards from dismantling – medium quality
Low-grade printed circuit boards	16 02 15* / 02-3	printed circuit boards from dismantling – low quality
Printed circuit boards	19 12 11* / 08-2	circuit board fraction
Cables	16 02 16 / 10	cables (mix)
	19 12 03 / 08-2	cable fraction
Motors	16 02 16 / 11	electric motors/dry transformers (mix)
	19 12 03 / 01-3 19 12 03 / 01-4	motors/transformers after shredding
Compressors	16 02 16 / 12	compressors (excl. oil)
Drives	16 02 16 / 17	hard discs, cd-rom-, dvd- and floppy drives
Lamps	16 02 16 / 19	lamps - no hazardous substances
ABS	19 12 04 / 03-1	plastics 'pieces' ABS 'pure'
PS	19 12 04 / 03-2	plastics 'pieces' PS 'pure'
PE/PP	19 12 04 / 03-3	plastics 'pieces' PE +/- PP
PVC	19 12 04 / 03-4	plastics 'pieces' PVC 'pure'
EPDM	N/A	N/A
PMMA	N/A	N/A
PU foam	16 02 11* / 02	mix of 'cabinets' containing PU foam insulation
	19 12 04 / 05-1a	PU foam < 0.2 % (H)CFC
	19 12 11* / 01	PU foam > 0.2 % (H)CFC
Other plastics parts	16 02 15* / 04	Plastics ‘parts’
	16 02 16 / 30	
	16 02 16 / 31	
	19 12 04 / 03-5	other specific kinds of plastics 'pieces'
Plastic/metal-compounds	19 10 05* / 04	metal/plastics mixtures
	19 10 05* / 05	plastics/metal mixtures
Flat panel display	16 02 15* / 08-2a	LC flat panel display 'panels'
Glass	16 02 15* / 08-3	glass 'parts' from flat panel displays

[9] Aluminium, copper, zinc, brass and other non-ferrous metals can also be included in non-ferrous metals

Material and components	Correspondance to WF-RepTool output fractions	
	code	**Name of the fraction**
	16 02 16 / 32	flat glass 'parts'
	16 02 16 / 38	glass 'parts' from flat panel displays
	19 12 05 / 01	glass 'pieces' 'pure'
	19 12 05 / 05	glass 'pieces' from flat panel displays
Wood	16 02 16 / 34-2 16 02 16 / 34-3	wood 'parts'
	19 12 07	wood 'pieces' 'pure'
Concrete	16 02 16 / 36	concrete 'parts' from dismantling
	19 12 09 / 02	concrete 'pieces'
Oil and liquid fuels	13 19 02 07*	Oil wastes and wastes of liquid fuels oil and concentrates from separation
Chlorofluorocarbons, HCFC, HFC	14 06 01*	chlorofluorocarbons, HCFC, HFC
Other organic solvents, refrigerants and propellants	14 06 02*, 14 06 03*	other halogenated solvents and solvent mixtures, other solvents and solvent mixtures
Toner cartridges, ink cartridges and ink ribbons	16 02 15* / 03	mix of toner cartridges, ink cartridges and ink ribbons
	16 02 16 / 37	toner cartridges
Lead batteries	16 06 01*	lead batteries
Ni-Cd batteries	16 06 02*	Ni-Cd batteries
Mercury-containing batteries	16 06 03*	mercury-containing batteries
Alkaline batteries	16 06 04	alkaline batteries (except 16 06 03)
NiMH batteries	16 06 05 / 01	NiMH batteries
Li-ion batteries	16 06 05 / 02	Li-ion batteries
Other batteries	16 06 xx(*) / 01-3 (open)	other specific kinds of batteries
Other material	16 02 15* / 20 (open) 16 02 16 / 80 (open) 19 12 12 / 01	other components/fractions from dismantling or sorting residues from separation

3.2.3 Data extraction from WF-RepTool reporting

In accordance with the method presented in section 2.7, Eco-systèmes extracted the data on RRR collected from their operators treating the WEEE flows 'flat panel display appliances' (for laptops) and 'large household appliances' (for washing machines).

For the case study, Eco-systèmes selected the three first step operators achieving the highest RRR with their downstream acceptors and analyzed their batch report data to determine the mass of the final fractions produced for the years 2013 and 2014. The mass of the share of the final fractions produced by treatment and which use is classified as recycled or recovered was divided by the mass of the corresponding material in the input of the WEEE flow.

Due to the method of dividing the mass of material produced by an operator by an average input composition of the input WEEE flow, for some of the operators, RRR over 100% were calculated. This is due to the variability of the input composition, e.g. some operators receive very plastic-rich input flows, so that they produce more recycled plastics than usually contained in the average input, which leads to a recycling rate for plastic over 100%.

To deal with that, we decided to replace the calculated operator-specific rates over 100% by rates of 100%. Of course, in reality RRR of 100% are not possible, because losses cannot be avoided during WEEE treatment. Rates of 100% can only be justified by the variability of the measured parameters and uncertainties of their measurement. For the total result, i.e. the average material-specific RRR calculated considering the rates of the selected operators, a 'generic loss' rate of 2% was agreed [69], so that the calculated material-specific RRR cannot exceed 98%.

The datasets collected during the methodology testing contain quantitative material specific recycling and recovery rates (including energy and other material recovery), but no qualitative information on the description and quality of the recyclates and materials used for recovery (section 5.2.4).

3.2.3.1 Laptops

The method was applied to calculate the calculated material-specific RRR of nine materials contained in laptops. Table 18 shows, for each material, the average RRR, the standard deviation of the three operator-specific RRR, the minimum and the maximum RRR.

Table 18: Calculated material-specific RRR for laptops [69]

Fractions and corresponding materials		**Calculated recycling rates**				**Calculated recovery rates**			
		Average	**Std dev**	**Min**	**Max**	**Averag e**	**Std dev**	**Min**	**Max**
Plastics	Thermo-plastics	92%	9%	82%	100%	96%	7%	82%	100%
Non-ferrous metals	Aluminium	98%	1%	98%	100%	98%	1%	98%	100%
	Copper	98%	1%	98%	100%	98%	1%	98%	100%
Ferrous metals	Steel	98%	1%	98%	100%	98%	1%	98%	100%
	Cast iron	98%	1%	98%	100%	98%	1%	98%	100%
Printed circuit boards		Extraction rate:							
		94%	6%	83%	100%				
Drives		82%	n/a	n/a	n/a	82%	n/a	n/a	n/a
Hard-disks		92%	n/a	n/a	n/a	92%	n/a	n/a	n/a
LCD panels		-	-	-	-	-	-	-	-

Following comments on the calculated material-specific RRR need to be added [69]:

1. **Thermoplastics**: More investigations (including improved traceability on downstream operations) would be needed to be able to differentiate the RRR per resin.
2. **Ferrous and non-ferrous metals** can be found in different output fractions of the interim technologies (sorted iron fractions, as well as complex fractions like cables or electric motors, etc). The RRR were calculated by aggregating the recycled quantities of ferrous and non-ferrous metals separated from all metal-containing fractions which use classified as 'recycled' and compared to the total input average quantity. The data do not allow a differentiated consideration of ferrous and non-ferrous metals.
3. The rate for **Printed circuit boards** is not the recycling rate, but the **extraction** rate of PCB in the interim technologies (ratio output mass of sorted PCBs divided by the mass of PCBs in the input flow). To calculate the material-specific RRR, the extraction rate needs to be multiplied by the RRR of the PCBs in the integrated smelter. They are calculated in section 3.2.3.3. (Table 20 on page 69).
4. The RRR for **drives and hard-disks** are based on the average "packages" created and periodically updated by Eco-systèmes in WF-RepTool, based on data on the composition of WEEE flows collected using the sampling and analysis methodology [67].
5. The **LCD panel** is only the glass sandwich containing the liquid crystals, excluding the PMMA diffuser, which is part of the thermoplastics. Currently, the operators are looking for outlets for LCD panels, and are storing them or treating them with technologies under development. Research projects are ongoing. The stored fraction are excluded from the calculation of WEEE recycling and recovery rates reported to public authorities.

Unfortunately, it was not possible to quantify the extraction rate for batteries from laptops. The reporting does not make the differentiation between laptops batteries and batteries coming from other products and it is expected that the extraction rate of laptop batteries is not the same than the extraction rate of batteries from other small devices [69].

The standard deviations of the RRR ranged between 1% for metals and 9% for thermoplastics. The variability of the operator-specific RRR can be explained by the fact that the recycling routes for plastics are currently under development.

3.2.3.2 Washing machines

Table 19 presents the calculated material-specific RRR of seven materials contained in washing machines.

Table 19: Calculated material-specific RRR for washing machines [69]

Fractions and corresponding materials		**Calculated recycling rates**				**Calculated recovery rates**			
		Average	**Std dev**	**Min**	**Max**	**Average**	**Std dev**	**Min**	**Max**
Mineral fraction	Glass, concrete and other mineral materials	73%	18%	56%	100%	73%	18%	56%	100%

Fractions and corresponding materials		Calculated recycling rates				Calculated recovery rates			
		Average	Std dev	Min	Max	Averag e	Std dev	Min	Max
Plastics	Thermo-plastics	62%	30%	35%	100%	69%	27%	35%	100%
Non-ferrous metals	Aluminium	96%	6%	86%	100%	96%	6%	86%	100%
	Copper	96%	6%	86%	100%	96%	6%	86%	100%
Ferrous metals	Steel	96%	6%	86%	100%	96%	6%	86%	100%
	Cast iron	96%	6%	86%	100%	96%	6%	86%	100%
Printed circuit boards		Extraction rate:							
		43%	31%	11%	100%				

The comments on thermoplastics, metals and PCB (comments 1 to 3) under Table 18 are also valid for the calculated material-specific RRR for washing machines presented in Table 19. Regarding the **mineral fraction**, glass and concrete have the same destinations in the treatment chains of the selected operators and the same RRR [69].

The standard deviations of the RRR ranged between 6% for metals and 31% for the extraction of PCB. These figures show that the variability can be high for the materials with lower recycling rates, with a lower share in the total input and/or for which recycling routes are currently under development.

3.2.3.3 Calculation of RRR for PCBs

Based on the information gathered about RRR for several fractions in the final technology (section 2.5.2.2) and the composition of PCBs in washing machines and laptops (Table 16), the RRR for PCBs from washing machines and laptops were calculated.

An exhaustive list of chemical elements was compiled. Their weight fractions were taken from several sources and element specific RRR were identified. The weight fractions of all elements did not sum up to 100 % due to the variations and uncertainties on the weight fractions. The sum of the weight fractions was normalized to 100 %. The different kind of (brominated) plastics (e-glass filled epoxy resin, silicate filled molding compounds, other plastics e.g. from connectors) are broken down to their chemical elements such as C, Si, Br or Sb due to different RRR for the elements. The estimations were provided to Aurubis for comments and complementation. The materials ending up in the slag are accounted as other material recovery because they replace other materials by being used as reducing agent. The slag is used as backfilling material which is not considered as recycling according to the waste framework directive [21]. For more information refer to section 2.5.2.2.

Table 20 and Table 21 show the results of the estimation.

Table 20: Assumed average composition of laptop printed circuit boards [39], [40], [85] and calculation of the RRR based on information from Nolte [85]

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
Ag	0.11%	Silver	95%	5%			100%
Al	5.0%	Slag		100%			100%
As	0.003%	Mostly into anode slime for precious metal production, where it is discharged and disposed as Arsenik; rest slag		10%		90%	100%
Au	0.06%	Gold	95%	5%			100%
Ba	0.56%	Slag		100%			100%
Be	0.01%	Slag		100%			100%
Bi	0.012%	Mainly lead dross (Sb rich), speiss, alloys; rest slag, recycling values estimated	80%	20%			100%
Cd	0.0001%	Crude zinc oxide: 50-80 %; rest in Slag, probably some Cd disposed; real recycling values unknown		100%			100%
Cl	0.10%	Crude zinc oxide, slag		100%			100%
Co	0.01%	Slag; some as contaminant into nickel sulphate		100%			100%
Cr	0.35%	Slag		100%			100%
Cu	19%	Copper cathode	95%	5%			100%
Fe	4%	Slag		100%			100%
Ga	0.001%	Slag		100%			100%
Mn	0.75%	Slag		100%			100%
Ni	0.60%	Nickel sulfate	90%	10%			100%
Pb	0.98%	Lead tin alloy, anode mud, crude zinc oxide	80%	20%			100%
Pd	0.02%	Platinum group metal solution	95%	5%			100%
Sn	1.60%	lead tin alloy	75%	25%			100%
Sr	0.04%	Probabaly into Slag; possibly also into crude zinc oxide		100%			100%
Ta	0.58%	Slag		100%			100%
Zn	1.60%	Crude zinc oxide; slag	50%	50%			100%
Glass							
SiO2	18%	Slag		100%			100%
B2O3	3%	Slag		100%			100%
K2O	0.2%	Slag		100%			100%
CaO	6%	Slag		100%			100%
MgO	0.35%	Slag		100%			100%

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
NaO	0.20%	Slag		100%			100%
Plastics							
C	30%	50% recycling and 50% as energy recovery		50%	50%		100%
Br	3.5%	Bromide solution	50%	50%			100%
Sb	0.30%	Lead dross (Sb rich), speiss	80%	20%			100%
Total	**95.13%**		**24%**	**57%**	**15%**	**0.002%**	**95%**
Normalized to 100%			**25%**	**59%**	**16%**	**0.003%**	**100%**

R: recycled; OMR: other material recovery; ER: energy recovery; LD: landfilled

Table 21: Assumed average composition of printed circuit boards of washing machines [39], [40], [73], [85] and calculation of the RRR based on information from Nolte [85]

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
Ag	0.005%	Silver	95%	5%			100%
Al	6.0%	Slag		100%			100%
As	0.0010%	Mostly into anode slime for precious metal production, where it is discharged and disposed as Arsenik; rest slag		10%		90%	100%
Au	0.002%	Gold	95%	5%			100%
Ba	0.007%	Slag		100%			100%
Be	0.0001%	Slag		100%			100%
Bi	0.005%	Mainly lead dross (Sb rich), speiss, alloys; rest slag, recycling values estimated	80%	20%			100%
Cd	0.00001 %	Crude zinc oxide: 50-80 %; rest in Slag, probably some Cd disposed; real recycling values unknown		100%			100%
Cl		Crude zinc oxide, slag		100%			100%
Co	0.002%	Slag; some as contaminant into nickel sulphate		100%			100%
Cr	0.20%	Slag		100%			100%
Cu	19%	Copper cathode	95%	5%			100%
Fe	9.5%	Slag		100%			100%
Ga		Slag		100%			100%
Mn		Slag		100%			100%
Ni	0.10%	Nickel sulfate	90%	10%			100%
Pb	0.22%	Lead tin alloy, anode mud, crude zinc oxide	80%	20%			100%

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
Pd	0.002%	Platinum group metal solution	95%	5%			100%
Sn	0.91%	lead tin alloy	75%	25%			100%
Sr	0.001%	Probabaly into slag; possibly also into crude zinc oxide		100%			100%
Ta		Slag		100%			100%
Zn	0.24%	Crude zinc oxide; slag	50%	50%			100%
Glass							
SiO2	18%	Slag		100%			100%
B2O3	3%	Slag		100%			100%
K2O	0.2%	Slag		100%			100%
MgO	0.35%	Slag		100%			100%
CaO	6%	Slag		100%			100%
NaO	0.20%	Slag		100%			100%
Plastics							
C	30%	50% as reducing agent; 50% as energy recovery		50%	50%		100%
Br	3.5%	Bromide solution	50%	50%			100%
Sb	0.10%	Lead dross (Sb rich), speiss	80%	20%			100%
Total	**96.04%**		**21%**	**60%**	**15%**	**0.001%**	**96%**
Normalized to 100%			**22%**	**63%**	**16%**	**0.001%**	**100%**

R: recycled; OMR: other material recovery; ER: energy recovery; LD: landfilled

The results show that 22-25 % of the mass of the PCB is recycled (and over 90 % of the material value [87]), around 60 % is recovered as other material, 16 % recovered as energy and 10-30 ppm is disposed of. Although the differences in RRR between laptops and washing machines results from the different compositions, the uncertainties of the weight fractions (and RRR) do not allow the general conclusion that compared to the laptop PCB more of the PCB of a washing machine is recovered as other material and less is recycled.

The RRR are derived from one specific process chain. Thus, the exact estimates do not apply to all smelters. Even though we consider that the order of magnitude are representative for the use of PCB in integrated copper smelters (section 2.8.1.2), the rates in other smelters may differ in details. The RRR of each chemical element need to check for other smelters.

Furthermore, there are still some open discussion points about the RRR and flows of elements, for example

- Recycling rates for precious metals, Cu and Pd are certainly over 90 %, more probably around 98 %. For the estimation, 95 % were chosen as a "compromise".
- The RRR for Bi are adapted from the RRR of Sb
- Some technology metals which are present in very low quantities in the products especially the hazardous and toxic materials, might be partially disposed of in the subsequent treatment of the products.

- Minor amounts of O and H (e.g. from plastics) are not extra accounted for
- It is not possible to distinguish the share of C (from plastics) used as reducing agent and the share used as fuel substitute

Because both BoMs are combined from several data sources, it is necessary to make additional chemical analyses of different PCBs to find representative ranges for each product category.

3.2.3.4 Critical raw materials

In this study, it was decided to set a special focus on cobalt from batteries, palladium from populated PCB and indium from flat panel display appliances. This section discusses about cobalt and indium as palladium is recycled in integrated smelters, so that the results presented in section 3.2.3.3 apply. The results presented in this section were compiled through analysing the literature and contacting experts from the industry.

3.2.3.4.1 Cobalt from batteries

According to Annex VII of the WEEE directive, batteries have to be removed from any separately collected WEEE. The batteries separated from WEEE shall then be treated as required by the Batteries Directive.

Batteries have been identified as a fundamental source of cobalt in WEEE [37], [62]. Lithium-ion batteries based on lithium cobalt oxide ($LiCoO_2$) which contain approximately 14% cobalt [88], account for the majority of cobalt consumption. Minor amounts of cobalt are contained in NiCd and NiMH batteries as well as in Li-ion batteries based on lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) [88]. In Europe, five companies treating waste batteries produce a cobalt-intermediate that needs further refining: Umicore [89], Recupyl [90], AkkuSer [91], SNAM [92] and Accurec [93]. In Europe, Freeport Cobalt [94] and Umicore [95] provide final cobalt refining services.

The recycling rate for cobalt from lithium-ion batteries at the Umicore process is more than 90 % [96]. This rate considers only final treatment and not losses related to the extraction of batteries out of the WEEE flow by the interim treatment technologies and battery sorting.

3.2.3.4.2 Indium from flat panel display appliances

So far, the CRM indium is not recovered from flat panel display appliances. Technically feasible and market-ready recycling processes are available [97]–[99], but they are not scaled up for economic reasons due to the very low revenues expected from the production of secondary indium.

Currently, the LCD panels are stored or treated with new technologies that are still evolving. So far, no data on the RRR achieved by these new technologies are available. Currently, the stored fraction is excluded from the calculation of WEEE recycling and recovery rates reported to public authorities [69].

3.3 Calculation of the recyclability and recoverability rates of products

3.3.1 Laptop

According to the formula presented in Table 3, the recyclability and recoverability rates for a product requires adding the shares of the materials according to the BOM multiplied with the calculated material-specific RRR.

The BOM of the laptop published by FEM / IUTA [76] and the average calculated material-specific RRR are summarized in Table 22. The table shows only the average without considering variability and uncertainties (section 5.4.3).

Table 22: BOM and average calculated material-specific RRR to calculate the recyclability and recoverability rates of laptops

Materials and components	Share according to BOM	Average calculated recycling rate	Average calculated recovery rate
Ferrous material	11%	98%	98%
Aluminium material	4%	98%	98%
Copper cable and material	0.4%	n/a[1)]	
Plastic	38%	92% for thermoplastics n/a for other plastics	96% for thermoplastics n/a for other plastics
Printed circuit board	16%	94%[2)] x 26%[3)] = 24%	94%[2)] x 100%[3)] = 94%
Battery	11%	n/a	
LCD panels	8%	Not considered in the calculation because of storage/new technologies under development	
Drives	8%	82%	82%
Hard Disk	4%	92%	92%

[1)] Cables are usually going to specific interim processes to separate plastic and metal (for instance copper). In the study, no data were collected on the specific RRR of plastics and metal from cables, which do not have to be the same than the RRR of other plastics and metal parts

[2)] Extraction rate presented in Table 18

[3)] RRR for PCB from laptop presented in Table 20

Due to the missing specific recyclability and recoverability rates of batteries, copper cable and material and plastics, it was not possible to calculate at product level the average recyclability and recoverability rates of laptops.

3.3.2 Washing machines

The BOM of the washing machine WM1 (representative of the medium-price segment) published by Ardente & Mathieux [51] and the average calculated material-specific RRR are summarized in Table 23. Like for laptops, the table shows only the average without considering variability and uncertainties (section 5.4.3).

Table 23: BOM and average calculated material-specific RRR to calculate the recyclability and recoverability rates of washing machines

Materials and components	Share according to BOM	Average calculated recycling rate	Average calculated recovery rate
Acryl-Butadien-Styrol (ABS)	1.7%	62%	69%
Aluminium	3.2%	96%	96%
Brass	0.1%	96%	96%
Cable	1.1%	n/a[1)]	
Chipboard	2.9%	n/a	
Concrete	31.7%	73%	73%
Copper	1.3%	96%	96%
Cotton with phenolic binder	0.7%	n/a	
Electronic Components	0.5%	43%[2)] x 22%[3)] = 9%	43%[2)] x 100%[3)] = 43%
Ethylen-Propylen-Copolymer (EPDM)	3.1%	n/a	
Glass	2.7%	73%	73%
Cast iron	1.8%	96%	96%
Polyacryl (PA)	0.02%	n/a	
Polymethylmethacrylat (PMMA)	0.004%	62%	69%
Polypropylen (PP)	0.2%	62%	69%
PP 20% mineral filler	0.6%	n/a	
PP 40% mineral filler	11.2%	n/a	
Polystyrene (PS)	0.3%	62%	69%
Steel	33.9%	96%	96%
Other materials	3.0%	n/a	

[1)] Cables are usually going to specific interim processes to separate plastic and metal (for instance copper). In the study, no data were collected on the specific RRR of plastics and metal from cables, which do not have to be the same than the RRR of other plastics and metal parts

[2)] Extraction rate presented in Table 19

[3)] RRR for PCB from washing machines presented in Table 21

Due to the missing average recyclability and recoverability rates of some materials, it was also not possible to calculate at product level the recyclability and recoverability rates of washing machines.

3.3.3 Comparison to recycling rates in literature

The estimated RRR were compared with values available in the literature.

The Technical Report IEC-TR 62635 [12] lists recycling and recovery rates of product parts which require selective treatment, of product parts with a single recyclable material, of product parts difficult to process and of product parts which go to a separation process for two scenarios.

1) Scenario for large household appliances derived from a study by the Korean Electronics Association
2) European scenario for large household appliances, small household appliances, IT and telecommunication equipment, consumer equipment. (values from 2005-2008, recovery routes with proven economic viability, representative vor the average situation within Europe until 2013)

The values of scenario 2 are coming from various sources and have been checked for representativeness at several WEEE treatment centers.

In Annex D of the WEEELABEX treatment standard [18], simplified assumptions on RRR for several complex parts are stated. Both IEC-TR 62635 and WEEELABEX consider losses along the treatment chain until the material is actually recycled or recovered.

Furthermore, default re-use, recycling and recovery rates for several materials are integrated in the MEErP tool [20].

Table 24 lists some of the estimated RRR for different materials in WMs and laptops in comparison to the values in scenario 2 of the Technical Report IEC-TR 62635 [12], the WEEELabex treatment standard [18] and the MEErP tool [20].

Table 24: Comparison of the calculated material-specific recycling and recovery rates to literature references [12], [18], [20]

Fractions and corresponding materials		**Recycling rate**					**Recovery rate**				
		Laptop	**WM**	**IEC 62635 Example 2**	**WEEELab. Annex D**	**MEErP**	**Laptop**	**WM**	**IEC 62635 Example 2**	**WEEELab. Annex D**	**MEErP**
Plastics	**Thermo-plastics**	92%	62%	ABS: 74%; PP, PE: 90 %	N/A	29%	96%	69%	ABS: 75%; PP, PE: 91 %	N/A	44%
Non-ferrous metals	**Aluminium**	98%	96%	91%	N/A	94%	98%	96%	91%	N/A	94%
	Copper	98%	96%	85%	N/A		98%	96%	85%	N/A	
Ferrous metals	**Steel**	98%	96%	94%	N/A	94%	98%	96%	94%	N/A	94%
	Cast iron	98%	96%	N/A	N/A		98%	96%	N/A	N/A	
PCB		26%	22%	14-18%	30%	50%	100%	100%	57-61%	60%	50%

First of all, the method of data collection differs between the four data-sets. Therefore, a direct comparison of values should be done with caution. IEC-TR 62635 [12] does not differentiate RRR according to different treatment categories, i.e. RRR are not product-specific. IEC-TR 62635 differentiates RRR according to different plastic types, which was not possible in this study. The recycling rates for aluminium and steel are quite similiar, whereas for copper IEC-TR 62635 states lower rates. In case of PCBs the recycling rates estimated in this study are within the spread of values of IEC-TR 62635 and WEEELabex (14-30 %), whereas MEErP states higher recycling rates. The recovery rates of PCBs as stated by IEC-TR 62635 and WEEELabex are much lower than this study estimated. The reason is probably that at least WEEELabex acts on the assumption that 40 % of the PCB is thermally disposed.

The comparison shows that

a) the methods for data collection and value estimation need to be similar to produce comparable material-specific RRR
b) a combination of values coming from different data sources in order to calculate the product RRR does not make sense because interdependencies between treatment processes are not reflected
c) a differentiation of RRR depending on the input WEEE flows is useful to increase the data validity.

3.4 Applicability to other product groups

The calculated material-specific RRR derived for laptops can be applied to the materials contained in all flat panel display appliances (LCDs) with screen sizes larger than 7 inch diagonal (monitors, laptops, tablets[10] and TVs) because they go in a special treatment line for flat panel display appliances [100]. The RRR do not apply for other ICT devices or small household appliances, because they do not undergo the same treatment. .

It is also possible to apply the calculated material-specific RRR for washing machines to other large household appliances such as ovens, boiler, and dishwasher [100], of course under consideration of their own BOM. The calculated material-specific RRR cannot be applied to cooling devices such as refrigerators and air-conditioning units, because they belong to a separate WEEE input flow and go into a special treatment line (EoL scenario) for “cold appliances”.

In general, the calculated material-specific RRR apply to the materials of all devices treated together. However, exemptions to this general rule may occur and require a case-to-case differentiation. For example, it may make sense to differentiate the battery extraction rates for different products treated together.

[10] So far, tablets are seldom found in the WEEE flow. There is also the option to treat them like mobile phones and smartphones, i.e. the battery is removed and the rest goes to the integrated smelter. In that case, the method used to calculate the RRR for PCBs would apply.

4 Feasibility of the database

The aim of this section is to formalize all the necessary activities needed to collect data (including the involvement of key stakeholders) and to maintain the database.

4.1 Activities for setting-up the database

The activities were clustered according to tasks like the building of the database structure and the production of the reference values. The activities required strongly depend on the decided broadness of the scope of the database: how many products and which WEEE flow should be covered by the database?

4.1.1 Activities to build the database structure and the user portal

A proposition of the database structure is presented in section 2.9 (Figure 10, p. 49). Further research to improve it and the implementation should be connected to other database projects and software for material efficiency and environmental assessments, to make sure that compatible data formats and database structures enable the exchange of reference values.

This includes:

- The database application WF-RepTool [33] to determine the recycling and recovery rates at end-of-life level
- National and pan-European databases stored at Eurostat (including Member State data returns for the WEEE Directive)
- The Minerals4EU knowledge data platform (EU-MKDP) (Minerals4EU, 2014), which is compliant to the INSPIRE directive (EC, 2007) and the First Urban Mine Knowledge Data Platform delivered by the ProSUM project [43]
- The European Platform on Life-Cycle Assessment and the European Life Cycle Database [101]
- The IEC 62474 database on material declaration (IEC 62474, 2014)
- The Substances Declarations and Conflict Minerals Database BOMcheck
- The International Material Data System (IMDS) of the automotive sector
- The freeware for material flow analysis STAN produced by the Vienna University of Technology

Work is needed to program the database, the portal and the functions for the use and maintenance of the database.

4.1.2 Activities to set priorities for the data collection

First of all, it has to be decided for which products and materials data should be collected first. Here several decision criteria can be taken into account

- Products relevant within the ecodesign policies and/or for ecodesign requirement
- Products with high content of critical raw materials or other materials especially relevant for policy, referring to research projects estimating the composition of WEEE flows and future demand of secondary raw materials (see also Table 7, p. 34)
- Availability of data, e.g. on RRR in reporting of WEEE compliance schemes

The necessary activities are to define the decision criteria and screen the available information to prioritise the products and materials.

4.1.3 Activities to collect representative bills of materials

In order to find a representative BoM for one product category (e.g. laptops), the average and standard deviation of the weights of a representative sample of the population (e.g. all laptop models in Europe sold in year X) should be measured. For complex assemblies (e.g. PCBs) a chemical analysis might be required. Data on product compositions can also be sourced from recyclers (e.g. smelters) or research projects. Indicative costs for a chemical analysis of the element composition of e.g. 600 g PCBs amount to 700 to 1500 Euros. Böni et al. [102] quantified the activities to fully disassemble and weigh the materials of several devices (Table 25). The costs for disassembly depend then on the labour costs. Additional costs arise for the acquisition of devices.

Table 25: Effort to collect bill of materials: time to disassemble and weigh the materials of devices [102]

Product	**Effort (time)**
TV > 40”	325 Minutes
TV 30 – 39”	237 Minutes
TV < 29”	166 Minutes
PC Monitor	106 Minutes
HDD Desktop PC	117 Minutes
HDD Laptop	99 Minutes

4.1.4 Activities to produce the reference values on RRR

The activities necessary to produce the reference values are:

1. identify operators and/or WEEE compliance schemes and/or other stakeholders willing, allowed and able to provide data
2. select the operators considered for the calculation of the material-specific RRR,
3. define the EoL scenarios,
4. analyze the composition of the input WEEE flows,
5. conduct batch analyses,
6. analyze the data and calculate the operator and material-specific RRR (per operator)
7. calculate the reference values, i.e. the material-specific RRR (average, standard deviation, ranges and/or other indicators) and
8. collect additional data

4.1.4.1 Identification of stakeholders providing data

The first step is to identify operators and/or WEEE compliance schemes and/or other stakeholders in Europe willing, allowed and able to provide data collected using the harmonized method. This requires contacting the stakeholders, explaining the project, presenting the benefits that they can expect, clarifying their needs and agreeing on the conditions and expectations related to their participation. Therefore, it is important to understand the limitations they encounter in their daily work and how those could be addressed be the database. The involvement of pro-active stakeholders is crucial to ensure the filling up of the database with useful and valid information. The stakeholders involved in this study named following reasons for participating:

- Taking influence on definitions
- Explaining possibilities and limitations of treatment processes
- Share knowledge and opinions along the treatment chain
- Getting insights into political and technological developments
- Making recyclability operational as a tool for eco-design

Here, meetings, interviews and/or workshops have to be planned. Key points to discuss are the classifications of fractions as recycled or recovered, the harmonisation of methods (e.g. batch and input analysis), the willingness to share data, and the confidentiality of data.

4.1.4.2 Selection of operators considered for the calculation of the material-specific RRR

In the methodology testing, we selected out of the "pool" of operators the three first step operators achieving with the downstream acceptors the highest RRR. This number of selected operators may be increased and different for the different WEEE flows (see section 5.2.3). The methodological research, based on statistical analysis of the available data from the operators and from one or more WEEE compliance schemes, to determine how many and on which criteria operators should be selected to optimize the validity of the calculated RRR, may require high efforts. As soon as the method is defined, the operators need to be selected for each considered WEEE flow [103].

4.1.4.3 Activities to conduct the batch analyses

Batch analyses are required by the WEEELABEX standard and by national regulations of some countries to determine the RRR. WEEELABEX requires batches for first step operators every 2 years (only cooling & freezing appliances every year) and for the downstream operators of external separation processes on non-pure fractions if this fraction represents more than 20 percent of the input (also in the frame of the 2-year batch, a batch every 2 years).

The French WEEE compliance scheme Eco-systèmes conducts each year around 70 batches of step 1 operators and around 20 batches of step 2 operators, which amounts to around 1100 tons of WEEE treated during all batches of one year [103]. The batch analyses comply with the requirements on batch analyses (e.g. amounts of input material) defined by the French Environment and Energy Management Agency (ADEME) and in annex C (requirements concerning batches) of WEEELABEX [18].

The batch analyses involve the auditors as well as the operators. A batch analysis requires preparation, the analysis itself (1 to 2 days per batch), and the data analysis and consolidation (e.g. using WF-RepTool).

4.1.4.4 Activities to analyse the composition of the input WEEE flows

The input analyses are needed to get data to compare with the shares of the final fractions classified as recycled and recovered measured through the batch analyses.

In accordance with the method adopted by Eco-systèmes to collect data on the composition of the WEEE flows [67], around 50 tonnes/year and over 150 different product types were sampled and analyzed during the first years to build a reliable database. After that, the sampling was prioritized for the maintenance and update of the database [103]. In order to cover the four WEEE flows treated (flat screens, small appliances, large cooling appliances, large non-cooling appliances), Eco-systèmes analyzes more than 150 different product types [103]. For each product type, a minimum of 30 devices are analyzed to get an average composition. For the product types which represent a high share of a flow, much more than 30 devices are analysed [103]. The collected data on the composition of the WEEE input flows is confidential and was not provided for the study. Other WEEE compliance schemes and research groups developed and update databases on the compostion of WEEE, e.g. [43], [44]. It could be helpful to keep information on the composition of the WEEE flow as parallel information to the RRR because the average composition is very important information regarding which materials are relevant.

4.1.4.5 Computer-based analysis of data to calculate the material-specific RRR

Based on the results of the batch and of the input analyses, the material-specific RRR can be calculated. Table 26 shows, exemplarily for the five WEEE input flows differentiated in the French system [104], which materials (as defined in section 2.4.2.2 and Table 5 and listed in the table Material Type of the database structure presented in Figure 10) are present in the WEEE flow. For the combinations of material and WEEE flow market with a cross, a material-specific RRR can be calculated. The table shows how many combinations of materials and WEEE flows can be counted, i.e. how many datasets are required in the database to cover all WEEE flows and materials.

Table 26: Presence of the materials for the WEEE flows according to the French classification of WEEE flows [104]

	Relevance for the WEEE flows				
Material	**Non-cooling LHA**	**Cooling LHA**	**SHA**	**Displays**	**Lamps**
Iron	X	X	X	X	X
Stainless steel	X	X	X	X	X
Aluminium	X	X	X	X	X
Copper	X	X	X	X	X
Zinc	(X)	(X)	(X)	(X)	(X)
Rare earths	X		X	X	X
Mercury-containing parts				(X)[11]	X
High-grade printed circuit boards			X	X	
Medium-grade printed circuit boards	X	X	X	X	X
Low-grade printed circuit boards	X	X	X	X	X
Cables	X	X	X	X	
Motors	X	X	X		
Compressors		X			
Drives			X		
Lamps	(X)	(X)	X	X	X

[11] Not in LCD displays with LED backlighting

Material		Relevance for the WEEE flows				
		Non-cooling LHA	Cooling LHA	SHA	Displays	Lamps
Plastics	ABS	X	(X)	X	X	(X)
	PS	X	X	X	X	X
	PE/PP	X	(X)	X	X	X
	PVC	X	X	X	X	(X)
	PU foam	X	X	(X)		
	Other plastics parts	X	X	X	X	X
Plastic/metal-compounds		X	X	X	X	X
Flat panel display		(X)	(X)	(X)	X	
Glass		X	X	(X)	X	X
Wood		X		X		
Concrete		X				
Oil and liquid fuels						
Chlorofluorocarbons, HCFC, HFC			X			
Other organic solvents, refrigerants and propellants			X			
Toner cartridges, ink cartridges and ink ribbons				X		
Lead batteries				(X)		
Ni-Cd batteries				X		
Mercury-containing batteries				(X)		
Alkaline batteries				X		
NiMH batteries				X	X	
Li-ion batteries				X	X	
Other batteries				X		
Other material		X	X	X	X	X

LHA: Large Household Appliances
SHA: Small Household Appliances
X: Material is present in the WEEE flow
(X): Material may be present in the WEEE flow

According to Table 26, 100 to 120 combinations of materials for the WEEE flows were identified as relevant, i.e. 100 to 120 material-specific RRR can be calculated. This number can be reduced, e.g. by grouping or neglecting the materials having very low mass shares, like zinc and rare-earth elements, or expanded by adding other materials or grouping the WEEE in more than 5 different WEEE flows. Therefore, the activities to determine the RRR strongly depend on the required level of details (number of WEEE flows, number of materials and components considered).

4.1.4.6 Activities to assess the validity of the reference values

Background research is needed to assess the validity and quantify the uncertainties of the reference values. So far, the standard deviation of the operator-specific rates selected to calculate the average RRR was considered as an indicator of the variability of the rates and of the uncertainty on the calculated average RRR (section 5.4.3), and the parameters influencing the validity are listed in Table 8. This list need to be further elaborated to better understand how the variability and the uncertainty of the measured parameters used for the calculation of the RRR influence its validity. Based on this understanding, different approaches can be compared with the aim of developing a method to describe the validity and quantify the uncertainties. The research would provide some information supporting the formulation of recommendations to improve the data validity.

4.1.5 Activities to collect additional data

Section 5.3 presents the needs for further research to collect data that are not collected yet in the frame of the determination of the RRR as required in the WEEE Directive, but would be useful to increase the validity of the calculated material-specific RRR. Following issues come into questions for the additional data collection:

4.1.5.1 Analysis of the batch input

Instead of using the average input composition to calculate the material-specific RRR, the input of the batch analysis could be analysed. To be useful, such data on input composition should be measured on a batch with the same composition than the batch used for the treatment assessment. In addition to the existing (and significant) burden associated with the batch treatment analyses, this would require a complex and time-consuming procedure for the operator to store significant quantities of WEEE to constitute two identical "representative" batches [103]. According to the requirements concerning batches (annex C) of WEEELABEX [18], the minimum amounts of input material for batches of small and large appliances are 50 tonnes in large shredders (for large appliances around 1000 units) and 10 tonnes in medium shredders (for large appliances around 200 units). The input material would need to be collected, stored and disassembled to weigh the materials. Orders of magnitude of the efforts for that are provided in time per device in Table 25 of section 4.1.3. An estimate for the disassembly of 200 large appliances and weighing of the materials is around 1200 hours of work.

Only a corresponding financing would possibly make such additional burden acceptable for the operator. The procedure would have to be replicated for each batch analysis which results are used for the calculation of the RRR, because due to the input variability the results from a batch are probably not transferable to another batch. This procedure seems hardly realistic [103].

4.1.5.2 Better differentiation of the materials

Section 5.3 shows that further data collection would be necessary to increase the granularity of the available data to better differentiate the materials, e.g. to differentiate the RRR of different plastics resins and non-ferrous metals. For that, some batch analyses at step 2, step 3 or step 4 operators are already carried out, but the available results do not necessarily provide the level of details needed for this specific use [103]. Confidentiality issues related to competitively sensitive information as well as technical and statistical challenges are barriers to the collection of the data.

4.2 Activities for maintaining the database

The database needs to be kept maintained and updated. This means updating:

1. the database structure and the user portal to comply with new functional requirements
2. the BOMs
3. the EoL scenarios

4. the calculated material-specific RRR based on a new selection of operators, the results of their recent batch analyses and the updated composition of the input WEEE flows

The activities to maintain and update the database structure and the user portal need to be estimated by the experts that develop them, based on the decisions taken.

As operators determine and report RRR annually, the reference values could, theoretically, also be updated annually. However, some data may just be copied from the previous year. How often batch analyses are made depends on the requirements of the WEEE compliance scheme. WEEELabex for examples requires "to determine recycling and recovery rates, batch processing […] shall be performed at least once every two years per site and per category" [18]. Due to the variations from one batch to another, data should be taken from two following years to estimate recyclability and recoverability rates.

For the BOMs, the EoL scenarios and the calculated material-specific RRR for each WEEE flow, the update can occur either:

- every year after the measurement and the reporting of the last RRR or
- every second year to be aligned with the requirements on batch processing of WEEELabex

The frequency of the update should depend on the product groups and on the materials. An update every second year might be sufficient for product categories for which "significant changes of the input quality" or "of the treatment technology" [18] are not expected. The update can address all materials or focus on some materials which RRR might be affected by changes of the EoL scenarios.

5 Discussion and recommendations

The aim of this chapter in to summarize and discuss the results presented previously, and propose options and recommendations to address identified challenges.

5.1 Opportunities and limitations offered by the reference values

The suggested approach can provide reference values on material-specific RRR to calculate recylability and recoverability rates for example to be used in the preparatory studies of the European Ecodesign Directive [22]. For this purpose, the database can provide, besides the harmonised reference values, transparency on used methods, data quality and availability. Moreover, the use of the yearly reported data on RRR provides a realistic and yearly updated picture of the achievements of the treatment technologies currently established in the industry for the calculation of recyclability and recoverability rates of products.

In general, the limitations of the database are the limitations of mass-based recyclability and recoverability rates as an eco-design indicator for improving the material efficiency. The suggested approach and the reference values can be used to calculate the mass-based rates, but cannot be used without restrictions to assess the recyclability of single products in order to set design requirements, because only the influence of the BOM is reflected by the reported data on RRR collected within this study, and not the influence of non-material related design decisions of individual products.

Even if recyclability targets are set, one has to keep in mind that this could lead to trade-offs, for example a higher recycling rate of one material can lead to a lower recycling rate of another more valuable or environmentally more important material. Here a pareto-optimum between different goals needs to be found, whereas this optimum will be dynamic since many parameters, for example commodity prices, are volatile.

5.2 Methodological issues related to the use of the reported recycling and recovery rates to calculate the reference values

5.2.1 Harmonization of the interpretation of the definition of recycling and recovery

This section discusses the need to harmonize definitions and their interpretation in order to be able to collect comparable data. The definitions of recovery[12] and recycling[13] according to the Waste Framework Directive [21] provide room for interpretation for the determination of RRR by treatment operators and the calculation of material-specific RRR. Section 5.2.1.1 illustrates the consequences of the different interpretations based

[12] 'recovery' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. [21]

[13] 'recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. [21]

on the example of the RRR of a laptop and section 5.2.1.2 describes the situation across Europe.

5.2.1.1 The effect of different interpretations of the definitions of recycling and recovery - the example of the RRR of a laptop PCB

The prevailing opinion in the current discussions during the development of the norm EN 50625 is that as soon as a material/chemical element is transferred to a product (which is e.g. registered as a REACH product) this material/chemical element is considered as recycled, independently of its real application [105]. The other interpretation is that there is the need to ask for the real application of the product (i.e. product is not used for backfilling operations (see exclusion of backfilling by the Waste Framework Directive [21]) or the products is used for other applications where product characteristics are not met).

In the calculation of the RRR of PCBs in Table 20 and Table 21, non-oxidized iron and aluminium which end up in the slag count as "other material recovery". They replace other materials (see definition of "recovery") by being used as reducing agent. In that case, the calculation of the PCB recycling rate of 25 % (Table 20) is valid because the slag, altough being classified as product (iron silicate sand) for other purposes [59], is used as backfilling material which is not considered as recycling by the definition of EN 50625 considering the Waste framework directive [21].

In the case of the smelter considered in this study, both the slag (iron silicate sand) and the crude zinc oxide are classified as products by REACH registration [59]. As comparison to Table 20, Table 27 shows an alternative calculation of the RRR for a laptop PCB. Here, all elements (i.e. iron, aluminium, SiO_2 and other chemical elements) that end up in both products count as "recycled". This is valid according to the first interpretation of recycling (element is ending up in a product). Here a recycling rate of 66 % is calculated (compared to 25 % in Table 20). Because the PCB share of weight at a laptop is relatively high, this difference has an impact on the product recyclability rate.

Table 27: Alternative calculation of the RRR of a laptop printed circuit board (all materials which end up in the products iron silicate sand (slag) and zinc oxide count as recycled)

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
Ag	0.11%	Silver	95%	5%			100%
Al	5.0%	Slag	100%				100%
As	0.003%	Mostly into anode slime for precious metal production, where it is discharged and disposed as Arsenik; rest slag	10%			90%	100%
Au	0.06%	Gold	100%				100%
Ba	0.56%	Slag	100%				100%
Be	0.01%	Slag	100%				100%
Bi	0.012%	Mainly lead dross (Sb rich), speiss, alloys; rest slag, recycling values estimated	100%				100%
Cd	0.0001%	Crude zinc oxide: 50-80 %; rest in Slag, probably some Cd disposed; real recycling values unknown	100%				100%
Cl	0.10%	Crude zinc oxide, slag	100%				100%
Co	0.01%	Slag; some as contaminant into nickel sulfate	100%				100%
Cr	0.35%	Slag	100%				100%

Material	Share in %	Product/Destination	R	OMR	ER	LD	Sum
Cu	19%	Copper cathode	100%				100%
Fe	4%	Slag	100%				100%
Ga	0.001%	Slag	100%				100%
Mn	0.75%	Slag	100%				100%
Ni	0.60%	Nickel sulfate	100%				100%
Pb	0.98%	Lead tin alloy, anode mud, crude zinc oxide	100%				100%
Pd	0.02%	Platinum group metal solution	100%				100%
Sn	1.60%	lead tin alloy	75%	25%			100%
Sr	0.04%	Probabaly into Slag; possibly also into crude zinc oxide	100%				100%
Ta	0.58%	Slag	100%				100%
Zn	1.60%	Crude zinc oxide; slag	100%				100%
Glass							
SiO2	18%	Slag	100%				100%
B2O3	3%	Slag	100%				100%
K2O	0.2%	Slag	100%				100%
CaO	6%	Slag	100%				100%
MgO	0.35%	Slag	100%				100%
NaO	0.20%	Slag	100%				100%
Plastics							
C	30%	50% other material recovery (reducing agent); 50% energy recovery		50%	50%		100%
Br	3.5%	Bromide solution	50%	50%			100%
Sb	0.30%	Lead dross (Sb rich), speiss	100%				100%
Total	**95.13%**		**63%**	**17%**	**15%**	**0.002%**	**95%**
Normalized to 100%			**66%**	**18%**	**16%**	**0.003%**	**100%**

This example shows (in comparison to Table 20) that the calculation of the RRR depends on interpretations of the definitions. Currently, expert groups working on standardization are discussing these possible interpretations with the aim of agreeing on one interpretation and harmonizing the methods. Their results need to be integrated into the methods used to calculate the material-specific reference values on RRR.

5.2.1.2 Need for harmonizing interpretations of the definitions in order to collect comparable data

Geographical location can create differences because of interpretations potentially affecting the RRR, for instance:

- The classification of the use of a final fraction in "final technologies" as recycling, recovery or disposal is not harmonised over the countries. Seyring et al. [106] report that non-uniform interpretations of the terms recovery and recycling across Member States cause difficulties in defining which facilities are classified as recovery/recycling facilities. For instance, outlets that are considered in France as backfilling, i.e. "disposal" following the WEEE Directive, are considered as "recycling" in some counties in Germany. That has a strong impact on the RRR knowing that for example mineral fraction represents nearly 15 wt.% of non-cooling LHA.

- Data on RRR are not measured in all European countries in accordance with the WEEELABEX standard and the standard EN 50625-1 [27]. For example, some countries like Germany (according to §22 (2) ElektroG [107], the German transposition of the WEEE directive) apply article 11 (2) of the WEEE directive and consider that "the achievement of the recycling targets shall be calculated […] by dividing the weight of the WEEE that enters the […] recycling […] facility […] by the weight of all separately collected WEEE" [108], whereas some WEEE compliance schemes in other countries like Belgium, the Netherlands, France, Spain or Italy are WF-RepTool users [109] and apply the definition of the waste framework directive, in which recycling is defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It […] does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" [21]. In the first definition, the input into the treatment facility is considered, and not the reprocessing into end-of-waste fractions and other fractions which use is classified as recycled. The second definition is the more holistic and sound definition of recycling and the one adopted in the WEEELABEX and EN 50625-1 standards, and implemented into WF-RepTool. An overview of the duty to keep records on "products and materials when leaving (output) the recovery or recycling/preparing for re-use facility" for selected Member States was published by Seyring et al. [106].
- Countries differ in the procedures used to determine the RRR (based on batch analyses and/or monitoring of the destination of the output fractions achieved). This is influenced by differences in the implementation of EPR principles, e.g. the presence or not of WEEE compliance schemes and the requirements set by authorities as well as their intentions on the way how to determine treatment results of WEEE.

In general, there are significant differences in data quality across Europe. Countries like Belgium, the Netherlands, France, Spain or Austria are known to report according to the WEEELABEX standard. The data quality in those countries and the Scandinavian countries is good [110]. In Germany, the data availability and quality depend on the recycling company and compliance scheme [110]. Data in other European countries might be of less good quality [110]. Besides the transposition of the directive into national laws (interpretation), the enforcement, which also significantly varies from country to country, plays a role on the data quality. Besides, the European Commission has currently no legal measures to enforce the national compliance with the recycling targets set in the WEEE Directive. Furthermore, in order to achieve higher RRR and comply with the targets set in the WEEE-Directive, there is the tendency to calculate RRR according to the definition of recycling in the WEEE-Directive [110]. More research is necessary to get an overview on the methods applied in all member states to determine the RRR and to make this information publicly available in order to discuss and harmonise them.

As shown in section 5.2.1.1, not only on national level but also on reporting level, the definitions of recovery and recycling according to the Waste Framework Directive [21] provide room for interpretation for the calculation of RRR results from real processes and the estimation of RRR. The harmonisation of the methods and interpretations conditions the use of reported data on RRR to calculate the recyclability and recoverability rates of products.

The WF-RepTool provides an harmonised methodological framework with which the use of a final fraction, respectively its shares of components, in final technologies is classified. By using the WF-RepTool structure, RRR may be determined in a harmonised way. The WEEE compliance schemes using WF-RepTool [109] apply this methodological framework, because WF-RepTool provides a calculation structure, helps to harmonize classifications and can improve the calculation traceability. This qualifies, in principle, the integration of the data on RRR into the database. However, also within this framework the classification rules provided have to be applied properly and have to be checked by a detailed control of reports. WF-RepTool provides the structure to collect the data but cannot ensure an equal quality and representativeness of the data [63]. The actual methods used to collect the data might still differ between operators and compliance schemes (e.g. batch and input analyses). It is important that users are trained on the correct use of the WF-RepTool and methods to collect the comparable data, because the quality of the data increases when the reports are compiled by advanced WF-RepTool users and are checked for plausibility [66]. Requirements for checks for plausibility are not defined in all countries, and the available requirements are not harmonized.

5.2.2 Selection and description of the EoL scenario

The generic end-of-life scenario describes the reference network of economically running treatment processes. The specific treatment technologies used to treat the WEEE (e.g. crushing technologies like shredders or smashers, conditioning technologies for plastics), as well as the order in which the technologies are used, can vary according to the operators.

As explained in section 2.6.2.1, the end-of-life scenario used to derive the calculated material-specific RRR should be based on an existing process chain and not design a theoretical treatment chain and combine data related to each link of this chain, because of interdependences (the performance of the second step processes cannot be measured without considering the first interim process, section 2.6.2.1). The separate consideration of the process steps would generate errors and less valid results by denying the dependency of the process steps. The selected operators should operate representative and economically running treatment processes using best available techniques for the WEEE flow in question (section 5.2.3).

After having understood and mapped the whole chain of treatment steps until the final technologies, the scheme for the EoL scenario should be generalised and simplified in such a way that it is valid for all selected operators. In some cases, it may be useful to define several groups of operators that apply different EoL scenarios.

5.2.2.1 Several EoL scenarios

In the cases that several EoL scenarios happen to be used by the WEEE treatment industry or there may be evidence that an alternative EoL scenario could become relevant in the next future [51], [73], this could be reflected by the selection of several alternative scenarios. For a given product, different EoL scenarios may be proposed to the user of the reference values, as presented for displays by Ardente et al. [111] (differentiation between manual and shredding-based processing). The RRR of the different alternatives should first be separately calculated.

This makes sense when it is not possible to define one single EoL scenario as the best available way (each EoL scenario has its advantages and disadvantages) and several alternatives reflect the reality in the recycling market. The relevance of proposing several EoL scenarios needs to be discussed case-by-case for the individual products. Possible criteria to estimate the relevance relate to:

- how established the different EoL scenarios are in the treatment industry,
- whether the EoL scenarios are economically running,
- how different they are,

- how high are the market shares of the different EoL scenarios
- if the differentiation of the EoL scenarios serves the goal of achieving progress towards eco-design and better recyclability of the products.

EoL scenarios can vary due to different factors including:

1. use of different technologies as a consequence of management decisions within the treatment company,
2. adaptation to the characteristics of the WEEE received for treatment and
3. adaptation to different requirements and constraints that drive the treatments like the availability of technologies and of downstream acceptors or market prizes for output fractions in.

An example of the co-existence of two economically running EoL scenarios concerns flat screens, for which dismantling and shredding are used in treatment facilities [111]. Currently, it is not foreseeable which processes will be most established in 5 years.

If it makes sense for the purpose of the assessment, several EoL scenarios could be weighted e.g. according to their relevance in the market to calculate "average" material-specific RRR. The relevance could be calculated as the mass fraction of waste products that undergo to the different typologies of existing facilities [6]. The feasibility of this procedure still needs to be tested, because this was not considered in the calculation of the recycling and recovery rates in the methodology testing (chapter 3).

To use higher recyclability and recoverability rates reached with an alternative end-of-life scenario, the user should also be required to prove that its products are actually treated following this specific EoL scenario. The choice of a scenario achieving higher product recyclability and recoverability rates has to be linked to conditions like the availability of the economically running treatment process, and/or of relevant information convincing treatment operators that applying e.g. a deeper manual dismantling would be economically beneficial. We suggest not to prescribe the use of certain treatment technologies or designs, but to set targets and/or require the proof (e.g. batch analyses) that alternative (higher or lower) recyclability and recoverability rates are reached by a certain end-of-life scenario and/or by a certain design.

5.2.2.2 EoL scenarios for new materials and products

Usually, at the time when new product technologies are introduced onto the market (such as LED backlighting for flat panel devices), specific treatment processes for those are not developed yet. Experience and data for the treatment of "new" materials (e.g. magnesium frame in laptops), new "components" (e.g. LED backlighting in flat display panels) or "new" products (e.g. tablets) might therefore not be available because they do not appear yet in the current WEEE flows. According to the IEC/TR 62635 [12], in this case a RRR of zero should be taken into account.

However, additional information can be collected through interviewing treatment operators (e.g. if they would be able to separate a dedicated material e.g. magnesium or any kind of plastics from e.g. a mixed fraction in the day-to-day treatment) or in-situ treatment trials in order to find out what would happen with the material/product if it appeared in the WEEE flow (i.e. in which final fractions it ends up and whether it is recycled/recovered in the final technology). In case promising treatment processes already have been developed but are not yet applied for a "new" material or component, an option is to exclude from the calculation of the overall product recyclability and recoverability rate the mass of that material/component (as it is currently the case for flat display panels stored for R&D projects [112]). Another option is to calculate or assume a material-specific RRR. In this case, it must be ensured that the corresponding treatment technologies are available and economically running at the time the "new" products, components and/or materials reach end of life (e.g. through waste legislation, producer responsibility or financial instruments).

To summarize, we propose the following rules to be discussed:

1) In case the current EoL scenarios are able to recycle or recover the new material, estimate the RRR through in-situ treatment trials and expert knowledge. The estimated RRR should be periodically revised.
2) In case there is no recycling process yet in development for the new material and the current EoL scenarios are not able to recycle or recover it, set the recyclability rate for this material to zero (this should encourage innovation for recycling)
3) In case a dedicated treatment process is under development

    a. The material could be excluded from the calculation of the product recyclability and recoverability rate, for instance if the new material has other environmental benefits (e.g. more reliable, substitution of a hazardous material, higher energy efficiency). This decision should be revised after a few years to check whether recycling processes were implemented in the meantime. If not, the material specific recyclability and recoverability rate should be set to zero.
    b. If a pilot process is available, the material-specific RRR of the pilot process could be calculated and used for the calculation of the recyclability and recoverability rate of the product. The RRR should be revised after a few years to check (1) the validity of the RRR and (2) whether recycling processes were implemented in the meantime. If not, the material specific recyclability and recoverability rate should be set to zero.

5.2.3 Selection of operators

In the case studies on laptops and washing machines, it was decided to select the three first step operators achieving the highest RRR with their downstream acceptors in order to retrieve RRR from operators using economically running best available techniques (BAT). Other options to define the number of operators to be selected and the selection criteria are presented in section 2.6.2. The definition of economically running treatment processes (section 2.4.1) should be discussed and refined before developing the database, under consideration (for harmonization purpose) of the wordings "representative EU recycling plants" as used in the Commission Implementing Decision C(2014) 10238 [24], and "recovery routes with proven economic viability" as used in the IEC/TR 62635 [12].

The number of selected operators, as well as the criteria to select them, can be experimentally changed to investigate the effects, e.g. of an increase of the number of selected operators on the calculated RRR and the standard deviation. In this study, a trial of calculating the RRR for the materials contained in washing machines considering five (instead of three) first step operators achieving the highest RRR with their downstream acceptors was done. Table 28 shows the average material-specific recycling rate, the standard deviation of the three or five operator-specific rates, the minimum and the maximum recycling rates. Table 29 presents the figures for the material-specific recovery rates.

Table 28: Calculated material-specific recycling rates for washing machines considering three operators (op.) like in Table 19 and five operators [69]

Materials	Average		Std dev		Min		Max	
	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.
Glass, concrete and other mineral materials	73%	75%	18%	16%	56%	56%	100%	100%
Thermoplastics	62%	49%	30%	31%	35%	2%	100%	100%

Materials	Average		Std dev		Min		Max	
	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.
Aluminium	96%	96%	6%	6%	86%	86%	100%	100%
Copper	96%	96%	6%	6%	86%	86%	100%	100%
Steel	96%	96%	6%	6%	86%	86%	100%	100%
Cast iron	96%	96%	6%	6%	86%	86%	100%	100%
PCB	Extraction rate:							
	43%	44%	31%	26%	11%	11%	100%	100%

Table 29: Calculated material-specific recovery rates for washing machines considering three operators (op.) like in Table 19 and five operators [69]

Materials	Average		Std dev		Min		Max	
	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.	3 op.	5 op.
Glass, concrete and other mineral materials	73%	75%	18%	16%	56%	56%	100%	100%
Thermoplastics	69%	55%	27%	32%	35%	2%	100%	100%
Aluminium	96%	96%	6%	6%	86%	86%	100%	100%
Copper	96%	96%	6%	6%	86%	86%	100%	100%
Steel	96%	96%	6%	6%	86%	86%	100%	100%
Cast iron	96%	96%	6%	6%	86%	86%	100%	100%

The results show little significant differences between the figures calculated using the rates reported by three and by five operators. The only significant differences regard the recycling rate of plastics (lower average considering five operators, the standard deviation remaining very high) and the extraction of PCBs (higher considering five operators, with a still high but lower standard deviation). For plastics, differentiating the resins could help, based on technical expertise, understanding the differences between the operator-specific RRR. So far, the high standard deviation seems to reflect the high variation of the plastic content and quality of the WEEE input flow, as well as the diversity of the used sorting and treatment technologies for plastics.

The trial did not allow recognising a general trend like the reduction of the standard deviation by selecting more operators, and therefore identifying a best approach to decide over the number of operators to be selected. For that, the trial would need to be replicated with other selections of operators to statistically analyse the effects of the selection on the average and the variability of the calculated RRR.

5.2.4 Required information about the treatment processes

In the methodology testing, we did not collect detailed information about the processes applied by the step 1 operator. One reason is the confidentiality of sensitive data on the technologies used by the operators; another is that this level of details was not necessary to calculate the material-specific RRR with the developed method, which is based on the RRR determined by several operators to comply with the reporting obligations. One disadvantage is that it impedes further analyses like the investigation of the influence of the used treatment technologies on the calculated material-specific RRR (e.g. manual or mechanical dismantling, stages of the treatment process at which specific fractions are sorted or separated), or the question whether design influences the choice of treatment process (e.g. manual extraction of a PCB or crushing) and thus the RRR. The RRR depend on other factors besides chosen treatment processes such as the availability of commodity markets and the quality requirements of the acceptors. The process chains are continuously adapted to these factors.

Data on recycling and recovery rates determined using WF-RepTool [109] are qualified, in principle, for the calculation of the material-specific RRR, because WF-RepTool provides a calculation structure aligned with the WEEELABEX and EN 50625-1 standards, helps to harmonize classifications and can improve the calculation traceability. However, WF-RepTool cannot ensure an equal quality and representativeness of the data [63]. The quality of the data increases when the reports are compiled by advanced WF-RepTool users and checked for plausibility [66]. The check of plausibility and a better understanding of the treatment processes are facilitated by a reporting with a high granularity, i.e. a stepwise approach to report each main treatment step (e.g. (1) dismantling, (2) shredding/separation and (3) further separation of fractions) as recommended by the WF-RepTool.

The data sets provided by Eco-systèmes for this study are based on a 'black box approach' of the whole treatment chain, where results of treatment operations from several treatment operators are summed up (different operators, different sites) and only the shares of final fractions leaving this whole treatment chain and which use in final technologies are classified as recycled or recovered are provided. Eco-systèmes provided further aggregated data, i.e. the reports were simplified by putting together e.g. all iron fractions without detailing neither their quality nor if the they were sorted manually or separated automatically after shredding. Black box approaches of reporting only the fractions leaving the whole treatment chain or the whole plant reduces the transparency and the possibilities for plausibility control. One reason for black box approaches mentioned by Eco-systèmes is the complexity of the processes, which the operators do not want to reflect into complex datasets. One other reason is the confidentiality of competitively sensitive information, which operators may not want to share and WEEE compliance schemes working with the operators data are not allowed to disclose. Two approaches are possible to deal with the confidentiality issue:

- accepting black box approaches in cooperation with the organizations controlling the quality of the data, i.e. not requiring more detailed information, or
- finding agreements (e.g. signature of non-disclosure agreements) with the operators and/or the WEEE compliance schemes to get access to relevant sensitive information (e.g. details on the treatment technologies, the composition of fractions, raw data from the batch analyses) and make sure that the needs for confidentiality are respected.

Both approaches have advantages and disadvantages and should be further explored. The first one reduces the needs for collecting sensitive data but also transparency. The second one requires more activities but opens doors to extended research to better understand the links between product design and recyclability. The decision to prefer one or the other requires discussion with the stakeholders willing, allowed and able to provide data.

An option would be not only to collect data on the quantitative recycling and recovery rates, but also to describe the shares of the final fractions which uses in final technologies are classified as recycled or recovered. For example, data could not only indicate that 60% of the plastics are recycled, but also that out of 100 kg of plastics in an input WEEE flow, e.g. 50kg of pure secondary PP and 10 kg of pure secondary ABS were produced by a plastics recycling technique as e.g. granulates for the market. This feature combined with the share of PP and ABS into 100kg of plastics in the input WEEE flow would be useful to calculate material-specific RRR.

The option to provide this information is partly foreseen in the WF-RepTool. For example, different kinds of plastics are named in the list of output fractions (annex 2) and the software provides a table called "calculation" listing the final fractions, their acceptors, the technology used and the masses of the final fractions which uses are classified as RU, R, ER and OMR.

If the WF-RepTool was chosen to measure the performance of the WEEE treatment for supporting the calculation of recyclability and recoverability of products, the choice of fractions and components to be differentiated in mixed fractions would have to be adapted. This might be done for a 'scientific WF-RepTool' parallel to the 'daily-use WF-RepTool' as asking for the list of output materials for each final technology in daily routine of reporting of RRR would overburden treatment operators providing data and WEEE systems controlling data [113]. Also Eco-systèmes [112] states that achieving this level of reporting is currently irrealistic, because it is much more demanding than the current reporting requirements, which are already a burden for the operators, and raises questions related to confidentiality. Apart from the burden associated to such detailed reporting, the availability of this detailed information is not guaranteed because of confidentiality issues [63].

5.3 Needs for further research

The needs for further research to collect totally or partly missing data are presented in this section.

In order to increase the granularity (defined here as the extent to which the data distinguishes different materials) of the available data, e.g. to differentiate the RRR of different plastics resins and non-ferrous metals, further data collection would be necessary. This kind of analysis would rely on step 2, step 3 or step 4 operators batch assessments (Eco-systèmes, 2015b). Some batch analyses of downstream operators are already carried out, but the available results do not necessarily provide the level of details needed for the calculation of the RRR (Eco-systèmes, 2015b). Confidentiality issues related to competitively sensitive information are a barrier to the collection of these data. Moreover, technical and statistical challenges need to be tackled. For example, the sampling and volumetry is hard to estimate, due to the varying composition and quality of the fractions produced by the step 1 operators and sent to the downstream acceptors (i.e.: various step 2 assessments needed for one output fraction of one step 1 operator), who use as an input a mix of fractions with different compositions coming from different step 1 operators („mix of plastics" coming from several step 1 facilities shredding and sorting different WEEE input flows). A solution would be to combine batch analyses with other approaches. One possible approach was used in this study to calculate the RRR of the PCB in section 3.2.3.3 based on the composition of the laptop and washing machine PCB and technical understanding of the processes taking place in the integrated copper smelter. This could also be done e.g. for plastics by getting data on the composition of the plastics flow going to plastics conditioning and determining which shares of the plastics in the input flows are classified as recycled (reprocessed into products, materials or substances) or recovered.

5.3.1 Plastics

Plastics recyclability is high in the (policy) agenda (e.g. plastics were defined as a priority area in the EU action plan for the Circular Economy [4]) and their share of weight in EEE is steadily increasing [110], so that plastics part design strongly influences the overall recyclability performances. In the provided reference values of this study, a differentiation between different resin types was not possible and thus no conclusion could be made on influence on the choice of the polymer on the RRR. One historical reason for the lack of reporting data on plastics conditioning and treatment is that plastics fractions from WEEE used to be traded before reaching the final recycling plant [69]. Nowadays, plastic acceptors in China exist which are certified by a German certification organisation and report RRR in compliance with the WEEE directive [114].

Strong activities and investments have been and are still made to develop both treatment technologies for plastics from WEEE and end markets for secondary plastics materials in some European countries. However, the availability of plastics treatment operators and end markets for secondary plastics materials are still unstable because of economic issues (market prices of (secondary) plastics depend on fluctuating oil prices) which influence the investment decisions for detection, sorting and treatment technologies. A (artificial) market demand could be created by requiring recycled content of plastics in new products. Moreover, the high variety of resins, the increased use of compound resins and missing information about which resins are used, makes sorting and separation for the recycler complex and costly [110]. New sorting procedures on BFR-containing plastics are currently tested and implemented. These developments will potentially be leading, in the coming years, to changes in plastics treatment performances [69].

Furthermore, the downstream traceability has to be improved. Batch analysis from downstream plastics conditioning companies (companies who separate plastics to different kinds of plastics and for different applications) have been obtained, but there is still a need to improve their representativeness (in time and between operators) and their accuracy to achieve a reliable evaluation of recyclability per resin type. Due to lack of traceability, it is also difficult to compare the resin specific masses of plastic classified as recycled by a plastic recycler who accepts plastic waste from different sources to the input analysis of one treatment category. Currently, the resins distribution in the WEEE input flow is very variable from an operator to the next one.

To get better data on RRR for different plastics resins, we suggest to:

- Collect data on the share of the different plastic resins in the input WEEE flows
- Collect data, for each WEEE flow, on the kinds and composition of the plastics fractions produced by the step 1 operators to better understand the potential for the downstream plastics treatment
- Cooperate with the acceptors of plastics fractions from WEEE (plastics conditioning companies) to
    1. list the technical possibilities to separate plastics and the options of application of mixed plastics and separated plastics (different kinds of plastics),
    2. to get a qualitative overview of the economically running possibilities to separate the polymers and their possible application as mixed plastics and as separated plastics (different kinds of plastics), and
    3. to discuss, design and conduct further experimental batch analyses to measure the shares of different kinds of plastics and plastics mixes which use is classified as recycled and recovered. These more in depth analysis may be done in the frame of the regular determination and reporting of WEEE treatment results

  The measurements should provide differentiated results for the different polymers and the different WEEE flows.

The activities should be connected to the work of the Commission towards the adoption of a strategy addressing the recyclability of plastics [4].

5.3.2 Complex parts

Some complex parts of WEEE may be delivered to different specialised treatment technologies (motors, cables, hard disk drives, etc.). They are not always reported in the same way by the operators. They can be reported 1) as a sorted fraction ("motor", etc.) being forwarded to next step treatment; 2) directly split between ferrous, non-ferrous and other non-metallic fractions; 3) a mix of 1 and 2. For example, it is possible that a share of the large motors from washing machines is separated manually and reported as "motors", whereas the remaining motors go into the shredding process, after which the ferrous metals and copper are separated and reported as metallic fractions. Cables are pre-treated to separate copper wire ending up at the copper smelter from cable sheath in order to treat the plastics.

In the reported data used within this study, the total separated quantities of ferrous and non-ferrous fractions are including the metallic part of these complex parts (and are compared to the total input of ferrous and non-ferrous metals in the input WEEE flow, including the metallic part of these complex parts). Eco-systèmes uses so-called "packages[14]" for these complex parts when they are sorted and specifically identified, by applying a generic composition and RRR determined by the WEEE compliance scheme [69]. These "packages" are used to ease the way of work.

The methods and data used to calculate the RRR of complex parts could be better harmonised, both at macro-scale (internationally) and at micro-scale (reporting habits of the operators). More harmonisation would improve the transparency and the traceability of the determination of the RRR for complex parts, and make more reliable data available.

5.3.3 Ferrous and non-ferrous metals

Ferrous and non-ferrous metals can be found in different output fractions ("pure" fractions, mixed fractions of e.g. non-ferrous metals and plastics and complex fractions like PCB, cables, electric motors, etc). Depending on the operator, the input WEEE flow and the used treatment technologies, the quantities and qualities of these output fractions are varying.

In the reference values generated by the methodology testing, the RRR for the group ferrous and non-ferrous metals are calculated together, i.e. the rates are calculated by aggregating the shares being classified as recycled or recovered of both ferrous as well as non-ferrous metals of all metal-containing fractions and divide those by the average quantity of metal in input. A differentiation between different non-ferrous metals like lead, tin, zinc, aluminium, copper and brass and ferrous metals like steel and iron could not be made by Eco-systèmes (although a differentiation between different metals in RepTool would be possible). The position of Eco-systèmes is that the estimation of metal specific RRR might be possible but tricky. Moreover, for the metals contained in WEEE which determine the price of the final fractions sent to downstream acceptors, such as copper, silver and gold and for the main metals such as iron, aluminium and steel, the operators of interim treatment facilities usually knows the composition of the products and the amounts classified as recycled [110]. This data could also be used to calculate the RRR [110].

Similar to the plastics and the complex parts, downstream traceability and batch analyses should be improved in order to differentiate RRR of different metals.

5.3.4 Mineral fraction

In the reference values used, the operators report that the use of a part of the mineral fraction is classified as recycled, i.e. that the mineral materials are "reprocessed into products, materials or substances whether for the original or other purposes [excluding] backfilling operations" (according to the definition of the Waste framework directive

[14] In WF-RepTool a package is a 'set' of treatment results defined by a 'name' and describing treatment results for a definite output fraction. Those "packages" are provided by the WEEE compliance scheme or the WEEE-Forum. [34]

[21]). It may be possible that other uses of mineral fractions have to be classified as recovered. It is important to carefully differentiate between recycling and recovery of the mineral fractions due to their high weight shares in e.g. washing machines.

5.3.5 Batteries

The extraction rate of batteries from electronics devices will differ depending on the type of device and its design (built in battery or removable battery). In case of a laptop, the removal of the battery is (was) usually easy. However, in newer models with slim design such as in ultrabooks or in tablets, batteries are often built in. Although the WEEE directive requires the removal of the batteries (extraction rate should be 100 %), this cannot be always ensured in reality. Real extraction rates are currently unknown. Here design decisions clearly influence the extractability.

We therefore suggest to further investigate the extraction rates of batteries in the frame of batch analyses by comparing the mass or number of batteries extracted with the mass or number of batteries contained in the input WEEE flow.[15]

If OEMs, or better standardised tests conducted by an independent organisation, cannot prove whether batteries can be extracted by the treatment operators, we suggest that the RRR for batteries should be set to zero.

After extraction, the batteries are sent to facilities that have to treat them in compliance with the battery directive. The battery directive requires reporting data on RRR. We suggest using these data to quantify the RRR of the extracted batteries, which should be differentiated according to different electrochemical systems.

5.3.6 Focus on substances like critical raw materials

The relevance of mass-based recyclability and recycling rates was criticised [6], [115], [116] because materials and substances embedded in small amounts in products little influence the mass-based rates, even though their recycling may be relevant from an economic, strategic and/or environmental perspective. Indeed, the critical raw materials were defined as a priority area in the EU action plan for the Circular Economy [4].

To address materials with low weight fraction (e.g. "minor" or "spice" metals, critical raw materials or plastics additives), the database, in principle, provides the possibility to:

- generate a list of the final fractions which use is classified as recycled and recovered, i.e. a list of secondary (critical) materials produced by the treatment with a short description of their quality (as mentioned at the end of section 5.2.4),
- calculate a substance-based recycling rates by dividing the mass of a substance embedded in a outcome of the treatment chain by the mass of the same substance that was embedded in the EEE.
- include specialized treatment technologies dedicated to the treatment of those materials

The study set a special focus on cobalt from batteries, palladium from PCB with components and indium from flat display panels. Although technologies were developed to recover indium from flat panel displays, currently only the recovery of cobalt from batteries and palladium from PCB with their components is economically running. In the

[15] However, the data used in this study stem from operators in France where the consumer is encouraged to remove the battery before collection. In this case, extraction rates and input analysis of battery contained in WEEE is not representative for the design and composition of the devices.

study, it was possible to determine the product/destination of the materials contained in PCBs, e.g. the CRM palladium (section 3.2.3.3).

In general, it is possible to collect similar information and data for other materials of interest. For the purpose of the improvement of product design, specific RRR targets for certain materials could be set in order to incentivise the 'design for recycling' or substitution of materials/components and the development of treatment processes (e.g. recovery of indium from flat displays).

5.4 How to deal with uncertainties

The material-specific RRR calculated for the case studies laptops and washing machines showed through the standard deviation and the differences between minimum and maximum values that for some materials like plastics, the calculated RRR vary considerably. Following main causes could be identified:

1. Variability of the input, for which average values are assumed to calculate the RRR
2. Differences in the treatment chain, i.e. the used interim technologies, their order and the used final technologies
3. Differences in the reporting conducted by the operators, e.g. regarding the complex parts

This section presents recommendations on methods for data collection to increase the data validity but make sure that the activities needed for data collection do not exceed a realistic limit.

5.4.1 Complexity of WEEE treatment

The (anyway complex) material composition of a WEEE input flow varies from a treatment plant to another, depending for instance of the geographical localization (e.g. heterogeneous deployment of heating/cooling EEE, socio-economic environment) and the type of collection points that supplies a treatment plant (e.g. older equipment are more often collected at municipal collection facilities than at retailers).

As already mentioned in section 2.8.2, the high variability of the WEEE input flow partly explains the variability of some material-specific RRR in the proposed approach, because the recycled amounts of a materials (determined through a batch analysis) is divided by the weight share of this material derived from a input analysis of another WEEE flow (same treatment category). Therefore, the weight of materials taken from the input analysis does not necessarily match the amount of materials of the batch which uses are potentially classified as recycled, recovered and disposed.

Also the "economically viable processes" may strongly vary in time, depending on a lot of parameters including the regulations and legal requirements applied to the operators, the availability of downstream acceptors, competitiveness of recyclates against raw materials, etc. Therefore, even for a given treatment chain, the RRR of the different materials may vary in time.

A "secret recipe" to deal with this complexity and variability does not exist. For all products, WEEE flows and materials, the applied methods and results need to be critically checked based on expertise on WEEE management systems including treatment technologies, in order to identify the cases that need specific data and data treatment. Plausibility checks that are anyway recommended for the determination of the RRR should be performed. An example related to the determination of the RRR based on batch analyses is the verification that the relation between mass of an output fraction yearly sent to a downstream process and the mass of treated input WEEE (e.g. 20% of the treated mass is sent to plastics conditioning) matches the relation between the mass of the same output fraction produced during the batch analysis and the mass of input WEEE treated during the batch analysis (e.g. the mass of the plastics mix fraction produced during the batch analysis represented 20% of the mass of the input of the batch analysis).

In addition to this permanent critical view on the calculations, a broad data sourcing, which involves, in a first step, many operators of interim and final technologies and/or WEEE compliance schemes from different geographical regions, helps to increase the data validity by enabling identifying the discrepancies between the RRR and by giving information to explain their origins. In a second step, an adequate selection of operators to be considered for the calculation of the RRR is necessary (see section 5.2.3).

5.4.2 Documentation

All the steps leading to the calculation of the material-specific RRR need to be well documented. For that, we suggest to create metadata describing the experimental methods used to measure the parameters used to calculate the RRR and listed in Table 8. The metadata should comply with the specifications of Dublin Core Metadata. "The Dublin Core" is a set of fifteen generic elements for describing resources: Creator, Contributor, Publisher, Title, Date, Language, Format, Subject, Description, Identifier, Relation, Source, Type, Coverage, and Rights [117]. Also the data validity needs to be discussed in the metadata, including an estimation of the spatial, timely and thematic representativeness of the reference values. The metadata should document for each step of the treatment chain (all interim and final technologies):

1. the procedure used to get the data
2. the estimated validity of the data and possible limitations, e.g. related to the representativeness.

5.4.3 Quantification of the uncertainties

Calculating one average material-specific RRR based on these different rates means reducing this complexity into one single figure that can be used by producers or policy makers for calculating the recyclability rates of products. So far, the standards, methods and research groups that published estimates of recycling rates (section 1.3.2) provided only one single average figure per material. However, this study clearly shows that a single figure does not reflect the variability and the uncertainties, so that it should be taken with caution and alternatives need to be discussed.

For this reason, the tables presenting the average material-specific RRR (e.g. Table 28 and Table 29) also show the standard deviation, the minimum and the maximum values of the data collected at the selected operators[16]. The standard deviations of the RRR ranged between 1% for metals from laptops and 31% for the extraction of PCB from washing machines. These figures showed that for some materials, for instance for the ones with lower recycling rates, with a lower share in the total input and/or the ones with recycling routes that are currently under development, the variability of the operator-specific RRR is high.

[16] The uncertainty on the RRR determined at one operator is unknown and would be complex to determine, because it depends on many factors related to the design of batch analyses and the variability of the input WEEE flow.

The standard deviation can be taken as an indicator of the variability of the rates. It can be assumed that the standard deviation correlates with the uncertainty on the average RRR. The results show for example that the uncertainty on the RRR is significantly lower for the chosen bulk metals than for the plastics, as separation of mixed plastics is challenging and not applied in all cases depending on regional and economic factors. However, the standard deviation does not directly reveal how high the uncertainty of the calculated material-specific RRR is.

Research to agree on the method used to quantify the uncertainties of the RRR is needed. Possible approaches are:

- To assume that the uncertainty is proportional to the standard deviation with an agreed proportionality factor. If this proportionality factor is 1, the range for the recyclability rates would be 97-99% for metals and 83-100% for thermoplastics from laptops.
- To define uncertainty classes, e.g. "high", "medium" and "low" uncertainty. For example, a "high" uncertainty could be assumed to amount to 10% of the RRR when the standard deviation is higher than 20%
- To base the uncertainty not (only) on the standard deviation, but also (or only) on the range, i.e. the difference between the maximum and the minimum rates measured at the selected operators

Once the uncertainty of the calculated material-specific is quantified, the question of how to consider it to calculate the recyclability and recoverability rates of products remains. One option is to use methods for error propagation to calculate the uncertainty of the recyclability and recoverability rates of the product based on the uncertainties of all used material-specific RRR. Another option is to base the calculation on ranges of material-specific RRR and to provide a "conservative", a "medium" and an "optimistic" recyclability and recoverability rate of the product. The "conservative" rate would consider the low bounds of the uncertainty ranges of the calculated material-specific RRR, the "optimistic" rate the high bounds, and the "medium" rates the average material-specific RRR.

6 Extension of the database and its applications

This chapter looks at the possibilities to integrate product design, WEEE collection and reuse into the scope of the database, to apply the database to other than EEE products and to expand the functionality to other environmental and economic indicators.

6.1 Extension of the scope of the database

6.1.1 Consideration of non-material related design features influencing the recyclability

The recyclability and recoverability of products are influenced by many parameters including the material composition of the product, the homogeneity of the components, their identifiability, the connections (affecting the extractability of the components), the standardisation of all these design-related factors, as well as the efficiency of the treatment processes and the technical and economic feasibility.

In the formula in Table 3, the only parameter considered to describe the product properties for the calculation of the recyclability and recoverability rates is the material composition in terms of bill of materials. However, the direct influence of non-material related design decisions of individual products (e.g. connections) cannot be derived from the reported data on RRR collected within this study, because the RRR employed in the examples stem from operators which process one treatment group (e.g. small household appliances, displays, non-cooling large household appliances) including products from different types, brands and models. The approach does not provide a dynamic assessment of the recyclability of specific individual products, i.e. does not allow reflecting how the choice of certain non-material related design features would affect the recyclability and recoverability rate.

However, a wider aim of the proposed approach is to incentivize design for recycling/recovery (D4R) in the frame of product policy, i.e. promoting design choices improving the recyclability and recoverability. For that, more information on the applied processes in the step 1 operator, their impacts on the treatment performance as well as the impacts of design decisions on treatment and thus on RRR has to be gathered. The real effect of design choices on recyclability and recoverability, i.e. the ability to separate and liberate the materials, could be investigated through qualitative and quantitative complementary approaches like real treatment tests and/or modelling and simulation (see for example [118]). This could also be used to "predict" the influence of future recycling processes on the RRR by testing liberation and separation behaviour in promising treatment processes in the research or pilot phase.

Based on that, the database could be expanded with additional EoL scenarios, or/and the list of materials could be expanded to specify design characteristics, e.g. to distinguish "PCB easily extractible" and "PCB not easily extractible". Through a **qualitative assessment** of the product design to check whether it fulfils key D4R requirements such as extractability and accessibility of pollutants/components (e.g. through a checklist or disassembly trial), the choice of different RRR could be justified.

If empirical (tested) and/or model-based data is available which proof the impacts of selected design decisions on the recyclability and recoverability rates, then those may be changed. The choice of a "better" EoL scenario, i.e. higher recyclability and recoverability rates, has to be supported by:

1. The availability of a proof, the e.g. a specific reverse logistic chain is in place for this specific product to end up in specialized treatment process or relevant information is available which show recyclers that for example a deeper manual dismantling would be economically beneficial

2. Showing that the WEEE treatment operators will apply the assumed EoL scenario to the product when it will become waste, i.e. that the process is or will be established and economically running. That implies clarifying who will have the burden of proving it. One possibility to make treatment processes economically running is to provide the operators with requirements for the treatment and financing.

For this process, it has to be clarified who has the burden of proof of the positive/negative effects of the product design on the recyclability and recoverability rates. This expansion of the database is associated with increased efforts for the data collection and lead to integrating into the database (qualitative) specific information on the properties of the products, beyond the BOM and the end-of-life scenario.

6.1.2 Collection as pre-requisite for WEEE treatment

Collection (collection rates but also the way of collection such as the mix of materials or the way of transport) have a high influence on the actual amount of recycled and recovered materials from products at their end-of-life. Estimates of collection rates were published by Huisman et al. [39] and Chancerel [119]. The general trend is that collection rates are higher for larger than for smaller appliances like mobile phones. Moreover, the constitution of collection groups mixing incompatible materials and components in a waste stream and inappropriate handling damaging the appliances have a negative effect on the treatment performance. To harmonize and improve the practices, WEEELABEX standards on collection and logistics [120] were created.

In this study, collection rates are not part of the calculation of recyclability and recoverability of products. Most factors influencing collection rates are not design-related, such as education and behavior of consumers or the capability of the people (or organization) collecting the waste. Considering the collection rates would reduce considerably the recyclability and recoverability rates of the products due to non-collected waste appliances. The rates would be less an indicator for material efficiency due to design and more an indicator measuring the performance of the WEEE management system for a certain WEEE flow and geographical area. Nevertheless, if that makes sense, the database could be expanded with product-specific collection rates. The collection data would have be provided by the organisations in charge for collection, which are not necessarily the stakeholders able to provide data on RRR (for instance operators and WEEE compliance schemes), depending on the national legislations.

6.1.3 Reusability

According to the WEEE directive [36], the weight of WEEE prepared for re-use counts for the determination of the recycling rate. So far, it has been decided that reusability rates of components are a priori excluded from this feasibility study, because EoL scenarios involving the re-use of components and appliances are currently marginal in the WEEE treatment system. However, not considering reusability for the assessment of the performance of a product regarding material efficiency does not encourage the producers to improve the reusability of their products, even though reuse has a higher position than recycling and other recovery in the waste hierarchy that shall apply as a priority order in waste prevention and management legislation and policy in the European Union [21].

We suggest not to exclude re-use from the reference values in general, but to enable in principle the consideration of EoL scenarios involving re-use in the database. Because preparing for re-use is part of recovery, this implies that the value of the calculated recyclability and recoverability rates is increased by the share of the re-usable parts or appliances.

6.2 Applicability to other products

The action plan for the Circular Economy of the European Union [4] states that "the Commission is putting forward new legislative proposals on waste to provide a long-term vision for increasing recycling", considering all waste. From the waste types mentioned in the action plan besides electronic waste, also packaging materials and end-of-life vehicles are complex waste flows for which reference values providing harmonised data to support the calculation of recyclability rates could make sense. This could also be done for batteries. For all these waste flows, the relevant legislation (Directive 94/62/EC on packaging and packaging waste, Directive 2000/53/EC on end-of life vehicles and Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators) sets mass-based recycling targets, which means that data on recycling rates are available, which could, in principle, be used for setting up and updating the reference values. Like for WEEE, harmonized procedures to calculate the RRR are lacking for the other waste streams, as shown by the recovery rates over 100% reported by Germany for the years 2010-2013 [121].

A first study to understand and classify the waste flows and the relevant materials and to propose a method to calculate the recyclability rates adapted to the characteristics of the waste flows and to the applied EoL scenarios would be necessary to investigate the feasibility and the usefulness of the reference values. Like for WEEE, the The feasibility study needs to take into consideration the past and current standards and activities related to recyclability, like the standard [26] listed in Table 4.

6.3 Use of the reference values for further environmental and economic assessments

In general, reference values on RRR can be used in environmental and economic assessments. Beyond the mass-based RRR, very useful data for environmental and economic assessments are the description and the mass of the final fractions produced by the treatment chain, which uses are classified as recycled or recovered.

The database will provide harmonised reference values on RRR that are applicable for calculations done according to several approaches and standards presented in Table 4. In particular, the reference values are useful for the calculation of the recyclability and recoverability rates in the MEErP (Methodology for the Ecodesign of Energy-related Products), the PEF (environmental footprint of products) and the REAPro method (Resource Efficiency Assessment of Product), which uses the indicator "Reusability/ Recyclability/Recoverability benefit rate". A metric combining the mass-based approach with environmental and economic assessment is the QWERTY concept of Huisman [122]. The use of those and other life cycle assessment based approaches in addition to the mass-based RRR enables assessing the environmental implications of the recyclability of products, especially targeting materials of low weight fractions, which hardly impact the mass-based indicators.

Another use of the reference values is to contribute to the improvement of the life-cycle inventory (LCI) data on end-of-life in public and commercial databases available to conduct life-cycle assessments (LCA) and other environmental analyses like exergy analysis. For instance the definition of the EoL scenarios for the products in the WEEE flows, the calculated material-specific RRR and, based on the BOM, the product-specific description and the mass of final fractions which use is classified as recycled or recovered bring relevant data for life-cycle inventories. However, the calculated material-specific RRR and the definition of generic EoL scenario are not sufficient to develop LCI, for which following critical information is necessary [63]:

- the detailed description of the whole treatment chain until the final destination of each fraction, including description and localization of all intermediary and final operations, which was not done and not necessary for this study (section 2.5.1)
- the identification of the exact destination of all fractions, including the ones which uses are not classified as recycled and recovered (e.g. losses in sorting processes) and that are not considered the database
- the description of the final applications, to assess the environmental benefits of the real material and energy substitution

A methodology for the calculation of recycling rates based on process simulation tools have been developed by Reuter et al. [123], [124]. In addition to the RRR, the commercial simulation tools provide simulation-based environmental indicators, exergy, the qualities and quantities of the recyclates, losses and emissions of materials during production and recycling. The results can be used as a basis for an Ecolabel succinctly communicating the salient details of the calculations to the consumer [124]. It would be very useful to compare the RRR calculated by the simulation tools to the ones calculated using the method proposed to calculate the reference values and to learn from possible discrepancies.

Recommendations for economic assessments were provided by the INEMi Repair and Recyclings metrics project [17]. It identified that one critical gap in most mass-based recycling metrics is the failure to include the economic realities of recycling. The potential of a product or material to be recycled does not mean it actually *is* recycled. In the proposed method in this feasibility study, the economic reality of recycling is indirectly included because the RRR stem from economically running treatment plants currently in operation. Therefore, the RRR in this study reflect reality.

Two main drivers which influence the economic reality were found by the INEMi Repair and Recyclings metrics project:

- Value of the recycled material: Can the material be recycled? Can it be sold?
- Cost of liberation/separation: Can the materials be separated into clean streams? What does it take to liberate the materials (hazardous materials included)?

Therefore, the report recommends two complementary approaches to estimate the recycling costs:

- Calculation of the net cost to recycle materials (revenues minus costs) and, therefore, the ability to assess whether a material is recyclable based on positive economics (in a free market driven by economic factors)[17].
- Identification of the most critical variables that estimate costs, especially those determined by product design, by developing a product design related semi-quantitative scoring system, which takes cost-influencing factors into account – such as difficulty to disassemble, type of interconnection, use of hazardous substances (depollution), etc.[18]

[17] The main issue when evaluating theoretically the recycling potential of a material by an economic modelling relies in the estimation of secondary material value. The magnitude of uncertainty related to the economic factors may be very high, and is influenced by the time gap between product designing and product end-of-life, i.e. recycling costs of future processes and future secondary material prices can hardly be predicted at the time of developing and designing the product. Moreover, with the implementation of regulations in a controlled market (Waste directive, WEEE directive, national waste policies, EPR schemes) establishing recycling targets, recycling is not only driven by economic factors. [127]

[18] The influence of the secondary material prices makes it particularly difficult to measure whether an "easier-to-disassemble" design will really lead to different RRR when the device will reach its EoL. Especially the time gap between product designing

With respect to the proposed database this means

- In order to implement a net-cost approach, a methodology to calculate economic recyclability of a given product based on the treatment costs of the end-of-life scenario and the revenues from the final fractions which use is classified as recycled and recovered needs to be developed. The proposed database could be expanded in order to include the relevant factors (e.g. treatment costs per kilogramm or commodity prices per kilogramm).
- The mass-based approach could be complemented by a semi-quantitative scoring system which takes cost-influencing factors into account.

Environmental and economic indicators/factors could be implemented in the future in the database to better assess the effect of a (change in the) product design, i.e. estimate the environmental/economic benefits and burdens of design decisions. This can help on the one hand legislators to improve eco-design policies, e.g. define certain requirements, and on the other hand help designers to improve their products with respect to recyclability and recoverability.

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and product end-of-life induces high uncertainty in the estimation of economic factors. Therefore, it may be very hard to assess on a reliable basis the effect of a change in the product design, and its cost-effectiveness. [127]

7 Summary of the recommendations

This section summarizes the main recommendations for policy, the reporting of recycling and recovery rates, the method and the extension of the scope which can support the use of reference values to calculate the recyclability and recoverability rate of a product.

Policy

- In order to be able to collect comparable data, definitions, methods to determine the reported RRR and classification of recovery and recycling have to be harmonized across different standards, national and European legislations and reporting schemes (see section 5.2.1).
- The setting up of reference values on RRR to support the calculation of recyclability and recoverability can encourage the stakeholders (producers, treatment operators and public authorities) to cooperate and innovate towards design-for-recycling and more performant WEEE treatment technologies
- Because proposed approach does not allow assessing the recyclability of individual products under consideration of non-material related design decisions, the approach should be accompanied with a describtive, qualitative assessment of the product's recyclability. To support this qualitative approach, the effect of design-decisions on the performance of the treatment processes should be tested in real-life or models. In case empirical or modelled data is available which proofs the positive/negative effect of non-material related design decisions on the RRR, this can be implemented in the reference values.

Reporting and WEEE compliance schemes

- The granularity of the collected data could be increased to get more differentiated information of material-specific recycling and recovery rates. Input and batch analysis as well as downstream traceability for critical materials, batteries, plastic resins, complex parts, batteries, ferrous and non-ferrous metals should be improved
- Shaping incentives to participate and dealing with confidentiality is very relevant for the calculation of the RRR, which relies on the willingness of the stakeholders (WEEE compliance schemes and operators) to provide data
- The data validity can be increased by broad data sourcing, common reporting praxis, good documentation and through plausibility checks by experts

Method and reference values

- Data should be derived from existing and representative "state of the art" treatment chains for the WEEE-flow in question, starting with the untreated WEEE until the end-of waste status is achieved or fractions are finally recovered or recycled. This is necessary for recording interdependencies between different process steps and operators.
- Only provide several alternative EoL scenarios with different associated reference values if
    - they have relevant market shares
    - the differentiation of the EoL scenarios serves the goal of achieving progress towards eco-design and better recyclability of the products
    - the user can prove that its products will actually be treated following an alternative end-of-life scenario achieving higher recycling and recovery rates
- For new materials or components, RRR should be set to zero in case it cannot be recycled or recovered by current treatment processes and there is no dedicated recycling process in development. In case there is a dedicated process in development, the weight of the material and component can be excluded from the calculation or the material specific RRR or the values of the pilot process can be used (see section 5.2.2.2).

- The RRR should be periodically updated

Extension of the reference values and work to be done

- Investigate the possibility to collect data on type and quality of the final fractions which uses are classified as recycled or recovered
- Investigation of methods to reflect uncertainties of the calculated material-specific RRR
- Assess possibilities to calculate material-specific recycling rates for critical materials, which due to their low weight share have negligible effect on the recyclability and recoverability rate of a product
- Assess the possibility to integrate re-use as part of recovery in the reference values
- Assess the possibility to use proposed approach for other waste flows such as packaging, batteries or end-of-life vehicles
- Assess possibilities to extend reference values with indicators on economic and environmental performance of recyclability and recoverability

8 Conclusion

The proposed method for the calculation of the reference values and the production of the reference values provides new opportunities to harmonize the measurement of the recyclability and the recoverability of products, even though the method is not yet a "turnkey solution" and several areas for which research is needed were identified. The method relies on the cooperation with stakeholders, for instance operators of treatment facilities, WEEE compliance schemes and experts involved in the efforts towards harmonisation of the determination of recycling and recovery rates like the expert group of the WF-RepTool.

The aim of the reference values, supporting the calculation of recyclability/ recoverability rates of products, provides a new perspective on the measurement of the RRR and their reporting, and opens the doors for new opportunities to link product design and recycling, as well as to enhance the dialogue between the stakeholders, for instance producers and treatment operators. This can create platforms to address, discuss and tackle challenges that are in the focus of eco-design policies focussing on material efficiency, like encouraging the use of best available treatment technologies and the anticipatory development of technologies to treat "new" materials that are contained in the products put on the market but not yet in the WEEE flows.

The setting-up of the reference values and the availability of data on RRR that can be used to calculate material-specific RRR depend on political issues like the European wide harmonization of the methods to determine, calculate and report the rates, which implies e.g. common interpretations of the definition of "recycled/recovered" across the national legislations and authorities.

Further research is needed to get more information on the influence of design decisions and chosen treatment processes on recyclability and recoverability rates, to get a more differentiated picture of the calculated material-specific RRR for some materials like plastics and non-ferrous metals and to better understand the extractability of batteries. On a more general level, methodological challenges could not be definitely solved in the frame of the feasibility study, e.g. how to calculate the recyclability and recoverability rates of "new" materials and components and how re-usability or economic and environmental sustainability can be considered in the database.

The developed methodology needs to be embedded in the current discussion on the relevance and the ability to implement recyclability and recoverability indicators, in order to concretise the use of the reference values for future product policy development towards more resource efficiency. Therefore, the further development of the reference values should be aligned to the industry driven activities in that direction (e.g. IEC TC 111 working group, group working on the CENELEC standard EN 50625, DigitalEurope's EcoDesign Group, iNEMI's Environmentally Sustainable Electronics TIG).

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List of abbreviations and definitions

BAT: Best available technique

BOM: Bill of materials

CCFL: Cold cathode fluorescent lamp

CRM: Critical Raw Materials

EC: European Commission

EEE: Electrical and Electronic Equipment

EoL: End-of-life

EPEAT: Electronic Product Environmental Assessment Tool

ER: Energy recovery

ErP: Energy-related Products

EU: European Union

EU-MKDP: Minerals4EU knowledge data platform

EWC: European Waste Catalogue

ICT: Information and communications technology

ILCD: International Reference Life Cycle Data System

IT: Information technology

JRC-IES: Joint Research Center – Institute for Environment and Sustainability

LCA: Life-cycle assessment

LCD: Liquid-crystal display

LCI: Life-cycle inventory

LD: Landfill disposal

LED: Light-emitting diode

LHA: Large household appliances

MEErP: Methodology for the Ecodesign of Energy-related Products

MFA: Material Flow Analysis

OECD: Organisation for Economic Co-operation and Development

OMR: Other material recovery

op.: Operator

PCB: Printed circuit board

PGM: Platinum-group metals

R&D: Research and development

REAPro: Resource Efficiency Assessment of Product

REE: Rare earth element

RRR: Recycling and recovery rate

RU: reuse

SHA: Small household appliances

Std dev: Standard deviation

TD: Thermal disposal

WEEE: Waste Electrical and Electronic Equipment

WM: Washing machine

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Annex 1: Classification of WEEE

Table 30: Classification of EEE according to the UNU keys [32]

Primary category	Sub-category		Main products/ comments	Collection category	WEEE forum category
	UNU key	Description			
Central Heating	0-01	Central Heating	Central heating on natural gas, geysers, boilers	0 CH	0 CH
Large household appliances	1-01	Professional (PROF) heating and ventilation	Excl. cooling equipment	A LHA	1A LHHA
	1-02	Dishwashers	Dishwashers	A LHA	1A LHHA
	1-03	Kitchen	Large furnaces, ovens, cooking equipment	A LHA	1A LHHA
	1-04	Washing machines	Washing machines, incl. combined dryers	A LHA	1A LHHA
	1-05	Drying machines	Wash dryers, centrifuges	A LHA	1A LHHA
	1-06	Room heating and ventilation	Household (HH) room heating + ventilation, excl. small (table) ventilators, hoods	A LHA	1A LHHA
	1-07	Sun beds	Sun beds and tanning equipment	A LHA	1A LHHA
	1-08	Fridges	Fridges for food, wine, ice, etc.	B C&F	1B C&F
	1-09	Freezers	Freezers for food, ice, etc.	B C&F	1B C&F
	1-10	Combined fridges and freezers	Combined fridges and freezers for food, wine, ice	B C&F	1B C&F
	1-11	Air conditioners	HH air conditioners, excl. large split-systems	B C&F	1B C&F
	1-12	C&F Other (Cooling and Freezing)	HH Dehumidifiers, ventilation w. cool., heat pump dryers	B C&F	1B C&F
	1-13	PROF C&F	PROF Air conditioners, fixed cooling installations, cooled displays and fridges	A LHA/ B C&F	1B C&F
	1-14	Microwaves	Incl. combination microwaves, excl. grills.	C SHA	1C SLHA

Primary category	Sub-category		Main products/ comments	Collection category	WEEE forum category
	UNU key	Description			
Small household appliances	2-01	Small HH	Incl. small ventilators, irons, time, scales, adapters. Etc.	C SHA	2 SHA
	2-02	Food processing	Kitchen and food processing, frying pans, cooking plates	C SHA	2 SHA
	2-03	Hot water	Coffee, tea, espresso makers, hot water, rice cookers	C SHA	2 SHA
	2-04	Vacuum cleaners	HH Vacuum cleaners	C SHA	2 SHA
	2-05	Body care	Tooth brushing, hair dryers, trimmers, razors	C SHA	2 SHA
IT and telecom equipment	3-01	Small IT&T	Small IT&T external components and accessories, incl. memory sticks	D IT	3A IT
	3-02	Desktop PC	Excl. monitors , accessories	D IT	3A IT
	3-03	Laptop PC	Laptops, notebooks, net books, tablets, excl. accessories	D IT	3A IT
	3-04	Printing and imaging	Scanners, printers, MFS, faxes, copiers	D IT	3A IT
	3-05	Telephones and equipment	Telephones and equipment	D IT	3A IT
	3-06	Mobile phones	Mobile phones	D IT	3A IT
	3-07	PROF IT	PROF IT equipment, servers, routers, data storage unit, incl. copiers, plotters	G PROF/ D IT	3A IT
	3-08	CRT monitors	Cathode Ray Tube Monitors	E1 CRT	3B IT CRT
	3-09	FPD monitors	Flat Panel LCD, LED Monitors	E2 FDP	3C IT FDP
Consumer equipment	4-01	Small CE	Small CE components, headphones, microphones	C SHA	4A CE
	4-02	Portable audio/ video	MP3, digital audio/video, e-readers, car navigation, etc.	C SHA	4A CE

Primary category	Sub-category		Main products/ comments	Collection category	WEEE forum category
	UNU key	Description			
	4-03	Radio and Hifi	Radio / Hifi sets, amplifiers, CD, tape, car audio	C SHA	4A CE
	4-04	Video and projection	VCR, DVD(R), projectors, incl. components	C SHA	4A CE
	4-05	Speakers	Speakers	C SHA	4A CE
	4-06	Camera	Camcorders, photo + digital cameras	C SHA/ D IT	4A CE
	4-07	CRT TVs	Cathode Ray Tube Televisions	E1 CRT	4B CE CRT
	4-08	FPD TVs	Flat Panel LCD, LED TV's	E2 FDP	4C CE FDP
Lighting equipment	5-01	Lamps	Other Lamps incl. halogen, Christmas, torches,	F Lamps/ C SHA	5A Lamps
	5-02	Compact fluorescent lamps	Compact fluorescent lamps, integrated and non-integrated lamps)	F Lamps	5A Lamps
	5-03	LED retro	Retrofit LED lamps, incl. halogen replacements	F Lamps	5A Lamps
	5-04	Straight tube fluorescent lamps	Straight tube fluorescent lamps	F Lamps	5A Lamps
	5-05	LED luminaries	Non retrofit LED lamps and fittings	C SHA	5B Lum
	5-06	Special lamps	Hg, Na (high + low pressure, street lighting)	F Lamps	5A Lamps
	5-07	Household luminaries	All HH luminaries and fittings, transformator, cable, sensors	C SHA	5B Lum
	5-08	PROF Luminaries	PROF Luminaries at offices, public space, industry.	A LHA/ C SHA	5B Lum
Electrical and electronic tools	6-01	Small Tools	All HH tools, soldering, energy, cleaning, drilling, sawing, etc.	C SHA	6 Tools
	6-02	Garden tools	All garden tools	C SHA	6 Tools
	6-03	PROF Tools	PROF large tools, excl. dual use ones)	G PROF	6 Tools

Primary category	**Sub-category**		**Main products/ comments**	**Collection category**	**WEEE forum category**
	UNU key	**Description**			
Toys, leisure and sports equipment	7-01	Small toys	Incl. trains, music instr. and other, excl. games + sports	C SHA	7 Toys
	7-02	Video game	Game consoles and external accessories	D IT	7 Toys
	7-03	Large toy	Large music instruments, sports and exercising)	G PROF	7 Toys
	7-04	PROF toy	PROF bowling alleys, non HH entertainment	G PROF	7 Toys
Medical devices	8-01	Small medical	HH blood pressure, thermometers, etc.	C SHA	8 Medical
	8-02	PROF medical	PROF hospital, dentist, diagnostics, treatment	G PROF	8 Medical
Monitoring and control instruments	9-01	Small monitoring	HH alarm, heat, smoke, measuring, security, excl. CRTs)	C SHA	9 M&C
	9-02	PROF monitoring	PROF monitoring equipment, garage, diagnostic, etc.	G PROF	9 M&C
Automatic dispensers	10-1	PROF dispenser	PROF non-cooled, hot drinks and food, coffee, tea, etc.	A LHA	10 Disp
	10-2	PROF dispenser	PROF cooled, vending food, bottles, cans, candy, etc.	G PROF	10 Disp

Annex 2: Classification list of output fractions – WF-RepTool

Table 31: Classification list of output fractions according to WF-RepTool (Dec. 2013) [125]

WF_RepTool code	structure	name - fraction
13 03 01*	insulating or heat transmission oils containing **PCBs**	heat transmission **oils** containing **PCBs**
13 03 07*	mineral-based **non-chlorinated** insulating and heat transmission oils	heat transmission **oils** not containing PCBs
14 06 01*	**chlorofluorocarbons,** HCFC, HFC	**CFC, HCFC, HFC** (step 1 &2)
14 06 01* / 01	CFC, HCFC, HFC **(step 1)**	
14 06 01* / 01-1		**CFC, HCFC, HFC, HC** (step 1)
14 06 01* / 01-2		**CFC, HCFC, HFC** (step 1)
14 06 01* / 02	CFC, HCFC, HFC **(step 2)**	
14 06 01* / 02-1		**CFC, HCFC, HC** (step 2)
14 06 02*	other **halogenated** solvents and **solvent mixtures**	
14 06 02* / 01		**compressor oil - halogen** content
14 06 03*	**other solvents** and solvent mixtures	
14 06 03* / 01		**NH3-CrO4**-mixture
14 06 03* / 02		**HC** (step 1 & 2)
14 06 03* / 03 (open)		other '**other solvents** and solvent mixtures'
15 01 01	paper and cardboard **packaging**	**paper/cardboard packaging** material
15 01 02	plastic **packaging**	**plastic packaging** material
15 01 03	wooden **packaging**	**wood packaging** material
16 02 09*	**transformers** and **capacitors** containing **PCBs**	
16 02 09* / 02		**PCB** (suspect) **capacitors**
16 02 10*	discarded **equipment** containing or **contaminated by PCBs** other than those mentioned in 16 02 09	**appliances** containing **PCBs**
16 02 11*	discarded **equipment** containing **CFC, HCFC, HFC**	
16 02 11* / 00		**mix** of **cooling & freezing appliances incl.** CFC/HCFC/HFC appliances
16 02 11* / 01		**CFC/HCFC/HFC** cooling & freezing **appliances**
16 02 11* / 02		**mix** of **'cabinets'** containing **PU foam insulation** *(all - CFC/HCFC and HC)*
16 02 11* / 02-1		**cabinets'** containing **CFC/HCFC-PU foam** insulation
16 02 11* / 03		CFC/HCFC **air conditioner appliances**
16 02 11* / 04		HFC **tumble dryer appliances**
16 02 11* / 05 (open)		other **appliances** containing **CFC, HCFC, HFC**
16 02 12*	discarded **equipment** containing **free asbestos**	**appliances** containing (free) **asbestos**

WF_RepTool code	structure	name - fraction
16 02 13*	discarded **equipment** containing **hazardous components** (2) **other than** those mentioned in 16 02 09 to 16 02 12	
16 02 13* / 01		**large (household) appliances** (**incl.** components to be removed)
16 02 13* / 02		**mix** of **non-CFC/HCFC/HFC** cooling & freezing **appliances**
16 02 13* / 03		**NH3** cooling **appliances**
16 02 13* / 04		**HC** cooling & freezing **appliances**
16 02 13* / 06		**CRT appliances** (**incl.** components to be removed)
16 02 13* / 07		**flat panel display appliances** (**incl.** components to be removed)
16 02 13* / 08		**grey good' / IT&T appliances** (**incl.** components to be removed)
16 02 13* / 09		**brown goods**' **/ consumer equipment** (**incl**. components to be removed)
16 02 13* / 10		**mobiles**
16 02 13* / 11		**small appliances** (**incl.** components to be removed)
16 02 13* / 12		**radioactive appliances**
16 02 13* / 13		other **'appliances' incl.** components to be removed
16 02 14	discarded **equipment other than** those mentioned in 16 02 09 to 16 02 13 (= **no** hazardous components)	
16 02 14 / 01		**large (household) appliances** shredder input (excl. components to be removed)
16 02 14 / 03	**cabinets'** with **no hazardous substances** in **insulation**	
16 02 14 / 03-2		**HC 'cabinets'**
16 02 14 / 03-3		**cabinets'** with **other** than **PU foam insulation**
16 02 14 / 04		**small appliances** shredder input (**excl.** components to be removed)
16 02 14 / 06		**appliances possible** for **re-use**
16 02 14 / 07		**appliances prepared** for **re-use**
16 02 14 / 08 (open)		other **'appliances'** (**excl.** components to be removed)
16 02 15*	**hazardous components removed** from discarded equipment	
16 02 15* / 01-2		**mercury** containing '**parts'** dismantled
16 02 15* / 02		**mix** of **printed circuit boards** from dismantling
16 02 15* / 02-1		**printed circuit boards** from dismantling - **high** quality
16 02 15* / 02-2		**circuit board 'chassis'** from dismantling
16 02 15* / 02-3		**printed circuit boards** from dismantling - **low** quality
16 02 15* / 02-4		**power supply units**
16 02 15* / 02-5		**printed circuit boards** from dismantling - **medium** quality
16 02 15* / 03		**mix** of **toner cartridges, ink cartridges** and **ink ribbons**

WF_RepTool code	structure	name - fraction
16 02 15* / 03-1		**toner cartridges** *(mix)*
16 02 15* / 03-1a		**ink cartridges** *(mix)*
16 02 15* / 03-3		**toner cartridges** and/or **ink cartridges** - **possible** for **re-use**
16 02 15* / 03-4		**toner cartridges** and/or **ink cartridges - not** possible for **re-use**
16 02 15* / 03-2		**ink ribbons** *(mix)*
16 02 15* / 04-1		**plastics 'parts'** from dismantling 'not pure' - **above** ROHS/REACH values
16 02 15* / 04-2		**plastics 'parts'** from dismantling 'pure' - **above** ROHS/REACH values
16 02 15* / 04-3a		**plastics 'parts'** dismantled from **TV's** 'pure' - **above** ROHS/REACH values
16 02 15* / 04-3b		**plastics 'parts'** dismantled from **monitors** 'pure' - **above** ROHS/REACH values
16 02 15* / 05-1		**asbestos** containing **'parts'** dismantled
16 02 15* / 05-2		**asbestos 'fibres'** separated
16 02 15* / 06	**CRT** - cathode ray tubes from dismantling	
16 02 15* / 06-2		**CRT 'tubes'** from dismantling
16 02 15* / 06-3		**mix** of **CRT glass 'parts'**
16 02 15* / 06-4		**cone glass 'parts'**
16 02 15* / 06-5		**front glass 'parts'** - uncleaned
16 02 15* / 06-6		**mix** of **CRT glass residues** from dismantling / splitting of tubes
16 02 15* / 07		**mix** of **gas discharge lamps**
16 02 15* / 07-1		straight fluorescent **tubes**
16 02 15* / 07-2		fluorescent light **bulbs** and **other formats**
16 02 15* / 07-3		**broken** gas discharge **lamps**
16 02 15* / 08		**mix** of **flat panel displays**
16 02 15* / 08-1		**mix** of flat panel display '**modules'**
16 02 15* / 08-1a		**LC** flat panel display '**modules'**
16 02 15* / 08-1b		**plasma** flat panel display '**modules'**
16 02 15* / 08-1c		**other** flat panel display '**modules'**
16 02 15* / 08-2		**mix** of flat panel display **'panels'**
16 02 15* / 08-2a		**LC** flat panel display **'panels'**
16 02 15* / 08-2b		**plasma** flat panel display **'panels'**
16 02 15* / 08-2c		**other** flat panel display **'panels'**

WF_RepTool code	structure	name - fraction
16 02 15* / 08-3		**glass 'parts'** from **flat panel displays** - **with** hazardous substances
16 02 15* / 09		components with **refractory ceramic fibres** - Beryllium and others
16 02 15* / 10		components with **radioactive substances**
16 02 15* / 11		**electrolyte capacitors**
16 02 15(*) / 13		**electron guns with** getter plates/pills
16 02 15(*) / 14		**getter** plates/pills
16 02 15* / 15		other **lamps** - **with** hazardous substances
16 02 15* / 17		**HCFC modules**
16 02 15* / 18		**mix** of **high value** metal/non-metal compound fractions from dismantling - **with** hazardous substances
16 02 15* / 19		**metal fractions** from dismantling - **with** hazardous substances/properties
16 02 15* / 20 (open)		other **components/fractions** from dismantling - **with** hazardous substances
16 02 15*/ 90		**residual waste** from dismantling - **with** hazardous substances and/or plastics **above** ROHS/REACH values
16 02 16	**components removed** from discarded equipment **other** than those mentioned in 16 02 15 (**no** hazardous components)	
16 02 16 / 01 ... 09	**metal fractions** from dismantling	
16 02 16 / 01		**iron-rich'** fraction from dismantling
16 02 16 / 02		**iron-metals** 'pure' from dismantling
16 02 16 / 03		**aluminium-rich'** fraction from dismantling
16 02 16 / 04		**aluminium-metals** 'pure' from dismantling
16 02 16 / 05		**copper-rich'** fraction from dismantling
16 02 16 / 06		**copper-metals** 'pure' from dismantling
16 02 16 / 07		**stainless steel-rich'** fraction from dismantling
16 02 16 / 08		**stainless steel** 'pure' from dismantling
16 02 16 / 09 (open)		other **metal fractions** from dismantling - **no** hazardous substances
16 02 16 / 10 ... 29	**metal/non-metal compound fractions -** dismantling	
16 02 16 / 10		**cables** *(mix)*
16 02 16 / 10-1		**power supply** cables
16 02 16 / 10-2		**inner** cables
16 02 16 / 10-3		**special** cables - demagnetization
16 02 16 / 10-4		**cables** excl. plugs
16 02 16 / 10-5		**plugs**
16 02 16 / 11		electric **motors**/dry **transformers** *(mix)*
16 02 16 / 11-1		**motors** - large

WF_RepTool code	structure	name - fraction
16 02 16 / 11-2		**motors** and **transformers** - small
16 02 16 / 12		**compressors** (excl. oil)
16 02 16 / 14		**connectors**
16 02 16 / 15		**deflection units**
16 02 16 / 16		**electron guns (without** getter plates/pills)
16 02 16 / 17		**hard discs, cd-rom-, dvd-** and **floppy** drives
16 02 16 / 19		**lamps** - **no** hazardous substances
16 02 16 / 20		**spare parts** - **possible** for **re-use**
16 02 16 / 21		**components/spare parts - prepared** for **re-use**
16 02 16 / 22		mix of **high value** metal/non-metal compound fractions from dismantling - **no** hazardous substances
16 02 16 / 23 (open)		other **metal/non-metal compound fractions** from dismantling - **no** hazardous substances
16 02 16 / 24		**capacitors** (not PCB suspect, not electrolyte)
16 02 16 / 30 ... 79	**non-metal fractions -** dismantling	
16 02 16 / 30		**plastics 'parts'** from dismantling 'not pure' - **below** ROHS/REACH values
16 02 16 / 31		**plastics 'parts'** from dismantling 'pure' - **below** ROHS/REACH values
16 02 16 / 32-1		**flat glass 'parts'** from dismantling 'not pure'
16 02 16 / 32-2		**flat glass 'parts'** from dismantling 'pure'
16 02 16 / 33		**front glass 'parts'** - cleaned
16 02 16 / 34-2		**wood 'parts'** from dismantling 'not pure'
16 02 16 / 34-3		**wood 'parts'** from dismantling 'pure'
16 02 16 / 36		**concrete 'parts'** from dismantling
16 02 16 / 37		**toner cartridges - no** hazardous substances
16 02 16 / 38		**glass 'parts'** from **flat panel displays** 'not pure' - **no** hazardous substances
16 02 16 / 39		**glass 'parts'** from **flat panel displays** 'pure' - **no** hazardous substances
16 02 16 / 40		**glass 'parts'** from dismantling - **no** hazardous substances
16 02 16 / 41 (open)		other **non-metal fractions** from dismantling - **no** hazardous substances
16 02 16 / 80 (open)		other **components/fractions** from dismantling - **no** hazardous substances
16 02 16 / 90		**residual waste** from dismantling - **no** hazardous substances and plastics **below** ROHS/REACH values
16 06 01*	**lead** batteries	**lead** batteries
16 06 02*	**Ni-Cd** batteries	**Ni-Cd** batteries
16 06 03*	**mercury**-containing **batteries**	**mercury**-containing **batteries**
16 06 04	**alkaline** batteries (except 16 06 03)	**alkaline** batteries (except 16 06 03)
16 06 05	**other** batteries and accumulators	**other** batteries and accumulators
16 06 05 / 01		**NiMH batteries**

WF_RepTool code	structure	name - fraction
16 06 05 / 02		**Li-ion** batteries
16 06 06*	separately collected **electrolyte** from batteries and accumulators	**electrolytes** from batteries and accumulators
16 06 xx(*) / 01	other specific **kinds** of **batteries**	
16 06 xx(*) / 01-2		**Li-**containing **batteries**
16 06 xx(*) / 01-3 (open)		other specific **kinds** of **batteries**
16 06 xx(*) / 02	other **mixtures** of **batteries**	
16 06 xx(*) / 02-1		mix of **batteries**
16 06 xx(*) / 02-2		(mix of) **'dry'** batteries
16 06 xx(*) / 02-3		mix of **rechargeable batteries** (accumulators)
16 06 xx(*) / 02-4		mix of **batteries** and accumulators from **pre-dismantling**
16 06 xx(*) / 02-5		mix of **batteries** and accumulators from/**after mechanical treatment**
19 01 17*	**pyrolysis wastes** containing **dangerous substances**	
19 01 17* / 02		fuels from pyrolysis and other special waste separation processes (e.g. cracking)
19 01 17* / 04		solid residues from pyrolysis and other special waste separation processes (e.g. cracking)
19 02 07*	**oil** and concentrates **from separation**	
19 02 07* / 01		**compressor oil** - **low** halogen content
19 02 07* / 02		**condensation water** incl. oil residues
19 02 07* / 03 (open)		other **oil** and concentrates from **separation**
19 10 01	**iron and steel waste**	
19 10 01 / 01		shredder **iron fraction** from large shredders
19 10 01 / 02 (open)		other **iron and steel waste** fractions from large shredders
19 10 02	**non-ferrous waste**	
19 10 02 / 01		**shredder non-ferrous fraction** - **no** hazardous substances and plastics **below** ROHS/REACH values
19 10 02 / 02		**metal/plastics** mixtures - **no** hazardous substances and plastics **below** ROHS/REACH values
19 10 03*	**fluff-light fraction** and **dust** containing **dangerous substances**	**shredder light fractions** - **with** hazardous substances
19 10 04	**fluff-light fraction** and **dust other than** those mentioned in 19 10 03 (**no** dangerous substances)	**shredder light fractions** - **no** hazardous substances
19 10 05*	**other fractions** containing **dangerous substances**	
19 10 05* / 01		**mix** of **non-ferrous** metal **shredder fractions** - **with** hazardous substances and/or plastics **above** ROHS/REACH values

WF_RepTool code	structure	name - fraction
19 10 05* / 01-1		**shredder non-ferrous fraction - with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 05* / 02		**heavy' shredder waste - with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 05* / 03		**sieving material - with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 05* / 04		**metal/plastics** mixtures - **with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 05* / 05		**plastics/metal** mixtures - **with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 05* / 90		**mix** of **shredder wastes** - **with** hazardous substances and/or plastics **above** ROHS/REACH values
19 10 06	other fractions **other** than those mentioned in 19 10 05 (**no** dangerous substances)	
19 10 06 / 01		**mix** of **non-ferrous** metal **shredder fractions - no** hazardous substances and plastics **below** ROHS/REACH values
19 10 06 / 02		**heavy' shredder waste** - **no** haz.sub. and plastics **below** ROHS/REACH values
19 10 06 / 03		**sieving material** - **no** haz.sub. and plastics **below** ROHS/REACH values
19 10 06 / 04		**plastics/metal** mixtures - **no** hazardous substances and plastics **below** ROHS/REACH values
19 10 06 / 90		**mix** of **shredder wastes** - **no** hazardous substances and plastics **below** ROHS/REACH values
19 12 02	**ferrous metals** fractions	
19 12 02 / 01	**iron** fractions	
19 12 02 / 01-1		**iron** fraction 'not pure'
19 12 02 / 01-2		**iron** fraction 'pure'
19 12 02 / 02	**stainless steel** fractions	
19 12 02 / 02-1		**stainless steel** 'not pure'
19 12 02 / 02-2		**stainless steel** 'pure'
19 12 03	**all' non-ferrous metals** fractions	
19 12 03 / 01	**non-ferrous metal** fractions with **Fe**	
19 12 03 / 01-1		**non-ferrous metals** with **iron** 'not pure'
19 12 03 / 01-2		**non-ferrous metals** with **iron** 'pure'
19 12 03 / 01-3		**motors/transformers after** shredding 'not pure'
19 12 03 / 01-4		**motors/transformers after** shredding 'pure'
19 12 03 / 02	**non-ferrous metal** fractions	
19 12 03 / 02-1		**mix** of **non-ferrous metals** 'not pure'
19 12 03 / 02-2		**mix** of **non-ferrous metals** 'pure'
19 12 03 / 03	**aluminium** fractions	
19 12 03 / 03-1		**aluminium** fraction 'not pure'
19 12 03 / 03-2		**aluminium** fraction 'pure'
19 12 03 / 03-3		**aluminium-iron** fraction 'pure'

WF_RepTool code	structure	name - fraction
19 12 03 / 04	**heavy' non-ferrous metals** fraction**s**	
19 12 03 / 04-1		**copper** and **grey metals mixtures** 'not pure'
19 12 03 / 04-2		**copper** and **grey metals mixture** 'pure'
19 12 03 / 05	**copper** and copper alloy fractions (**'orange'**)	
19 12 03 / 05-1		**copper** and **copper alloys** 'not pure'
19 12 03 / 05-2		**copper** and **copper alloys** 'pure'
19 12 03 / 06	**grey non-ferrous metals** fractions	
19 12 03 / 06-1		non-ferrous metals **grey** 'not pure'
19 12 03 / 06-2		non-ferrous metals **grey** 'pure'
19 12 03 / 07	**grey non-ferrous metals**- 'pure'	
19 12 03 / 07-2		**lead** 'pure'
19 12 03 / 07-3		**zinc** 'pure'
19 12 03 / 07-5 (open)		other **grey metals** 'pure'
19 12 03 / 08	**non-ferrous** metal **'compound' fractions - no** hazardous components	
19 12 03 / 08-2		**cable** fraction
19 12 04	**plastics** and **rubber - below** ROHS/REACH values	
19 12 04 / 01	**plastics** and **rubber** mixtures - **below** ROHS/REACH values	
19 12 04 / 01-1		**plastics** and **rubber 'pieces'** 'not pure' - **below** ROHS/REACH values
19 12 04 / 01-2		**plastics** and **rubber 'pieces'** 'pure' - **below** ROHS/REACH values
19 12 04 / 02	**hard plastics 'pieces' - below** ROHS/REACH values	
19 12 04 / 02-1		**hard plastics 'pieces'** 'not pure' - **below** ROHS/REACH values
19 12 04 / 02-2		**hard plastics 'pieces'** 'pure' - **below** ROHS/REACH values
19 12 04 / 03-1		plastics 'pieces' **ABS** 'pure' - **below** ROHS/REACH values
19 12 04 / 03-2		plastics 'pieces' **PS** 'pure' - **below** ROHS/REACH values
19 12 04 / 03-3		plastics 'pieces' **PE +/- PP** 'pure' - **below** ROHS/REACH values
19 12 04 / 03-4		plastics 'pieces' **PVC** 'pure' - **below** ROHS/REACH values
19 12 04 / 03-5 (open)		other specific **kinds** of **plastics 'pieces'** 'pure' - **below** ROHS/REACH values
19 12 04 / 04	**plastics** and other **organic fibres**, plastics **below** ROHS/REACH values	
19 12 04 / 04-1		**plastics** and other **organic 'fibres'** 'not pure' - plastics **below** ROHS/REACH values
19 12 04 / 04-2		**plastics** and other **organic 'fibres'** 'pure' - plastics **below** ROHS/REACH values
19 12 04 / 05-1a		**PU** foam < 0.2 % (H)CFC
19 12 04 / 07	**specific plastics mixtures**	
19 12 04 / 07-1		**cable plastics**
19 12 05	**glass**	
19 12 05 / 01		**glass 'pieces'** 'pure' - **no** hazardous substances

WF_RepTool code	structure	name - fraction
19 12 05 / 02		**front glass 'pieces'** 'pure' - cleaned
19 12 05 / 03		**tube glass** from **gas discharge lamps** 'pure' - cleaned
19 12 05 / 04		**glass 'pieces'** from **flat panel displays** 'not pure' - **no** hazardous substances
19 12 05 / 05		**glass 'pieces'** from **flat panel displays** 'pure' - **no** hazardous substances
19 12 05 / 06		other **glass fractions** - **no** hazardous substances
19 12 07	**wood 'pieces' - not** containing dangerous substances	**wood 'pieces'** 'pure'
19 12 09	**mineral fractions** (for example sand, stones)	
19 12 09 / 01		**mineral fraction** 'not pure'
19 12 09 / 02	**mineral fractions** - 'pure'	
19 12 09 / 02-1		**concrete 'pieces'** 'pure'
19 12 09 / 02-2		**concrete 'fines'** 'pure'
19 12 09 / 03	other **inorganic fractions**	
19 12 09 / 03-1		**inorganic 'fines'** 'not pure'
19 12 09 / 03-2		**inorganic 'fines'** 'pure'
19 12 10	**combustible waste** (refuse derived fuel)	
19 12 10 / 01		mixture of combustible wastes - conditioned for incineration - **no** hazardous substances and plastics **below** ROHS/REACH values
19 12 10 / 02		**mix** of **plastics** - conditioned for incineration - **no** hazardous substances and plastics **below** ROHS/REACH values
19 12 10 / 04		**toner material** - conditioned for incineration - **no** hazardous substances
19 12 11*	**other wastes** (including mixtures of materials) from mechanical treatment of waste containing **dangerous substances**	
19 12 11* / 01		**PU foam** > 0.2 % (H)CFC
19 12 11* / 02	**plastics** from separation - **above** ROHS/REACH values	
19 12 11* / 02-1		**hard plastics 'pieces'** 'not pure' - **above** ROHS/REACH values
19 12 11* / 02-2		**hard plastics 'pieces'** 'pure' - **above** ROHS/REACH values
19 12 11* / 02-3		**plastics** and other **organic 'fibres'** 'not pure' - plastics **above** ROHS/REACH values
19 12 11* / 02-4		**plastics** and other **organic 'fibres'** 'pure' - plastics **above** ROHS/REACH values
19 12 11* / 02-5		**plastics** and other **organic 'fines'** 'pure' - plastics **above** ROHS/REACH values
19 12 11* / 03	**glass** pieces or fines - **with** hazardous substances	
19 12 11* / 03-1		**mix** of **CRT glass 'pieces'** - uncleaned

WF_RepTool code	structure	name - fraction
19 12 11* / 03-2		**mix** of **CRT glass 'pieces'** - cleaned
19 12 11* / 03-3		**cone glass 'pieces'** - uncleaned
19 12 11* / 03-4		**cone glass 'pieces'** - cleaned
19 12 11* / 03-5		**front glass 'pieces'** - uncleaned
19 12 11* / 03-6		**mix** of **CRT glass residues** from mechanical treatment
19 12 11* / 03-9		**tube glass** from **gas discharge lamps** - uncleaned
19 12 11* / 03-10		mixtures of **mixed glass** and **other materials** from **gas discharge lamps** 'not pure' - uncleaned
19 12 11* / 03-11		**mixed glass** from **gas discharge lamps** 'pure' - uncleaned
19 12 11* / 03-12		**mixed glass** from **gas discharge lamps** 'pure' **-** cleaned
19 12 11* / 03-15		**glass 'pieces'** from **flat panel displays** - **with** hazardous substances
19 12 11* / 04	**coating materials - with** hazardous substances	
19 12 11* / 04-1		**fluorescent coating material** - **CRT's**
19 12 11* / 04-2		**fluorescent coating material** - **gas discharge lamps** - **with** mercury
19 12 11* / 04-3		**fluorescent coating material** - **gas discharge lamps - no** mercury
19 12 11* / 04-4		(fluorescent) **coating material** - **flat panel displays**
19 12 11* / 04-5		**sludge** from separation of **flat panel displays**
19 12 11* / 04-6		fluorescent **coating material-glass** mixture - **CRT's**
19 12 11* / 04-7		fluorescent **coating material-glass** mixture - **gas discharge lamps** - **with** mercury
19 12 11* / 04-9		**rare earths** containing fraction
19 12 11* / 05	**mercury** containing fractions separated	
19 12 11* / 05-3		**mercury** separated 'not pure'
19 12 11* / 05-4		**mercury** containing **fractions**
19 12 11* / 05-5		**mercury** separated 'pure'
19 12 11* / 06		**toner material** - **with** hazardous substances
19 12 11* / 08	**metal/non-metal compound** fractions - **with** hazardous substances	
19 12 11* / 08-1		**cable** and **circuit board fraction**
19 12 11* / 08-2		**circuit board fraction**
19 12 11* / 08-3 (open)		**other metal/non-metal compound** fractions from mechanical separation - **with** hazardous substances

WF_RepTool code	structure	name - fraction
19 12 11* / 09	**metal** fractions - **with** hazardous substances	
19 12 11* / 09-1		**iron** fraction - **with** hazardous substances
19 12 11* / 09-2		**aluminium** fraction - **with** hazardous substances
19 12 11* / 09-3		mix of **non-ferrous metals** - **with** hazardous substances
19 12 11* / 09-4 (open)		other **metal fractions** from mechanical separation - **with** hazardous substances
19 12 11* / 80		**residues** from **separation** - **with** hazardous substances and/or plastics **above** ROHS/REACH values
19 12 11* / 81		**shredder/separation waste - with** hazardous substances and/or plastics **above** ROHS/REACH values
19 12 11* / 82		**dismantling/shredder/separation waste** - **with** hazardous substances and/or plastics **above** ROHS/REACH values
19 12 12	**other wastes** (including mixtures of materials) from mechanical treatment of wastes **other** than those mentioned in 19 12 11 (= **no** dangerous substances)	
19 12 12 / 01		**residues** from **separation - no** hazardous substances and plastics **below** ROHS/REACH values
19 12 12 / 01-1		**plastics-/other organic** or **mixed 'fines'** 'not pure' - plastics **below** ROHS/REACH values
19 12 12 / 01-2		**plastics-/other organic** or **mixed 'fines'** 'pure' - plastics **below** ROHS/REACH values
19 12 12 / 02		**shredder/separation waste** - **no** hazardous substances and plastics **below** ROHS/REACH values
19 12 12 / 03		**dismantling/shredder/separation waste** - **no** hazardous substances and plastics **below** ROHS/REACH values
20 01 25	edible oil and fat	edible **oil** and **fat**
20 03 01	mixed **municipal waste**	mixed **municipal waste**

Annex 3: Classification list of technologies – WF-RepTool

Table 32: Classification list of technologies used according to WF-RepTool (Dec. 2013)

i or f	technology used	remarks - technologies used
first interim	dismantling / sorting	manual **dismantling** of components and **sorting** of WEEE/components for specific further treatment
first interim	large shredder / separation	typical large **shredder** (e.g. car shredder), **including dismantling** of components before shredding, **including** typical **internal separation** like e.g. air separation, magnetic separation, handpicking of fractions (e.g. motors), eddy current separation, sieves,...
first interim	shredder for cooling & freezing appliances / separation	**shredder** for 'cabinets' of **cooling & freezing appliances** (step 2), **including 'step 1' treatment** like dismantling and de-pollution steps, sorting of appliances etc., **including** typical **internal separation** like e.g. air separation of PU foam, magnetic separation, eddy current separation, flue gas treatment, ...; in case including **step 3** like **HC/(H)CFC** incineration or (H)CFC splitting and neutralisation or similar
first interim	medium shredder / separation	**medium shredder** e.g. WEEE specific shredding/grinding equipment like e.g. 'chain grinder', granulator,..., **including dismantling** of components before shredding +/- **sorting** of components after shredding, **including** typical **internal separation** like magnetic separation, eddy current separation,...
first interim	spec.treatm. of gas discharge lamps	end plate separation or crushing methods to **separate gas discharge lamps** to fractions for further treatment (e.g. further separation) or 'final processes' (e.g. glass, aluminium, coating material, Hg, residues) *(if first step of treatment is 'sorting' of lamps / non-lamps, use dismantling/sorting)*
interim	fine shredder / separation	**fine shredder** e.g. specific for WEEE fractions like cable shredders, **including** typical internal **separation** like e.g. magnetic separation, air tables,...
interim	separation	**separation processes** for mixed fractions from shredding/grinding - **all kinds** of **separation processes** like e.g. electromechanical, optical separation and separation on base of specific weight; e.g. separation processes or combinations of magnetic drums/belts, heavy media separation, floatation, air table separation, water table separation, blow out technologies, ...; mainly to be used for **mixed metal fractions**
interim	pyrolysis, cracking or similar	pyrolysis and other/similar special waste separation processes, e.g. cracking and/or separation under specific environment conditions - e.g by heat, vacuum, with catalysts; separation of e.g. used oil, plastics or other organic fractions or mixed, metal-containing WEEE fractions; production of **oils/derivates** for **fuel substitution**, metals separated for metal recovery
interim	manual separation	**manual separation** of **compound fractions** (see e.g. cable splitting) *(not to be used for simple sorting - see manual sorting)*
interim	manual sorting	**manual sorting** of **fractions** e.g. sorting of mixed metal fractions, handpicking of components from metal fractions,... *(see sorting by technical processes = separation)*
interim	CRT splitting / crushing	splitting of CRT **'tubes'** (e.g. hot wire technology or cutting technologies) or crushing/grinding processes of whole tubes, including or excluding **cleaning processes** for glass (e.g. 'vacuum cleaner' technology or any physical cleaning)
interim	CRT glass grinding / cleaning	crushing/grinding of **CRT glass fractions** including or excluding **cleaning** and/or **separation** of CRT glass (e.g. crushing of CRT glass 'parts' after 'splitting' technology, physical cleaning processes)

i or f	technology used	remarks - technologies used
interim	other glass conditioning	crushing/grinding and separation of **other glass** than CRT glass, e.g. treatment of **flat glass** from dismantling ... to achieve 'final glass fractions' for 'final processes' (e.g. for glass production)
interim	mineral conditioning	crushing/grinding and **separation** of ('not-pure') **mineral fractions** like e.g. concrete parts ... to achieve 'pure', 'final' mineral fractions for 'final processes' (e.g. for concrete production)
interim	plastics conditioning	pre-cutting / further **separation** / cleaning of **plastics** from dismantling or mechanical separation processes to **achieve** pre-sorted, cleaned = **'conditioned'** plastics **fractions** ('defined quality classes') for further separation (additional/next step plastics conditioning) or 'final processes' like e.g. * plastics recycling * definite use in other technologies (e.g. co-incineration, etc.)
interim	conditioning of high caloric material	cutting / separation / mixing processes to achieve **high caloric materials** e.g. for use in co-incineration
interim	conditioning of waste	mixing process to use any waste material (e.g. PU, wood residues etc.) to **prepare/solvent/stabilise wastes** before next treatment steps
interim	wood conditioning	cutting / **separation** of ('not-pure') **wood fractions** ... to achieve 'pure', 'final wood fractions' for 'final processes' (e.g. use in co-incineration,...)
interim	spec.treatm. of radioactive appl./comp.	e.g. **dismantling** of **components** to separate radioactive parts
interim	spec.treatm. of asbestos appl./comp.	e.g. **dismantling** of **components** to separate asbestos parts or fibres and/or any kind of immobilisation of asbestos appliances or components before 'final disposal processes'
interim	spec.treatm. of flat panel display appl./comp.	**dismantling** or **special shredding** or **crushing** methods of/for **flat panel display appliances** and/or flat panel display **components** like 'modules' and/or 'panels', including **further treatment** (e.g. separation) of flat panel display fractions
interim	special separation of rare earths	special **separation** processes for **rare earths**
interim	spec.treatm. of Hg-components	e.g. **manual dismantling** of **Hg-components** (e.g. to achieve mercury separated, glass, residues)
interim	Hg distillation - separation	**distillation plants** for **Hg-components** or **Hg-contaminated material** to separate mercury from other substances (e.g. to achieve mercury separated, coating material excl. Hg and/or glass, plastics, residues)
interim	spec.treatm. of toner cartridges	e.g. **sorting** of reuse-able toner cartridges (e.g. for refill) and/or **dismantling,** emptying, shredding/**separation** of non-reuse-able toner cartridges (e.g. to toner material, plastics, ...)
interim	battery sorting	**sorting** of 'mixed' batteries from dismantling to different kinds of batteries for battery treatment (e.g. Hg-, NiCd-, Pb-, Li-, NiMH-batteries and (remaining) alkaline batteries)
interim	battery separation	e.g. **emptying** and further **separation** of e.g. 'wet'-lead batteries to acid, Pb, plastics, residues,...
interim	preparing for re-use	sorting and **selecting** of appliances (see WEEE Directive II from phase 2) or components (e.g. spare parts, toner cartridges) for possible preparing for re-use; checking, cleaning, **testing** (function and security test) and/or repairing and **labelling** of appliances or components for re-use
final	re-use appliances	to **provide tested** and **labelled appliances** for **re-use**, i.e. via different sales structures like re-use shops or networks, incl. **warranty;** appliances are used for the **same purpose** for which they were conceived

i or f	technology used	remarks - technologies used
final	re-use components	to **provide tested** and **labelled WEEE components** (e.g. spare parts, re-filled toner cartridge) for **re-use**, i.e. via different sales structures like re-use shops or networks, incl. **warranty;** components are used for the **same purpose** for which they were conceived *(estimation that end-of-waste reached)*
final	steel mill 'traditional'	**steel mill** with any **traditional** technology, which has **no approval** to use plastics as reductant or for fuel substitution
final	steel mill 'special'	**steel mill** with any **special** technology and an **approval** that the use of organics can be classified as 'use as reductant' and/or 'use for fuel substitution'
final	stainless steel works	**stainless steel works**
final	Cu smelter 'traditional'	**Cu smelter** with **traditional** 1st step technologies for input fractions e.g. converter technology -> plastics will burn off at surface (= to be classified as thermal disposal)
final	Cu smelter 'special'	**Cu smelter** with any **special**-technology and an **approval** that the use of organics can be classified as 'use as reductant' and/or 'use for fuel substitution'
final	Al smelter	**Al smelter**
final	Pb smelter	**Pb smelter**
final	other metal smelters	**different** other **smelters** like e.g. Sn-, Zn- smelter
final	final processes for rare earths	special **final processes** for **rare earths** containing fractions
final	CRT-glass production	only to be used for **CRT-glass production**
final	glass production	production of **glass**, **glass products** or **glass applications** e.g. flat glass, foam glass, any definite glass (also special Pb-glass like e.g. x-ray glass), glass (tubes) for gas discharge lamps,...
final	production of other products of/with glass	production of **other products** of or with **glass** e.g. production of mineral wool, blasting material, cutting material, glass particles for paints, glass tiles, glass bricks, glaze etc.; **glass** as **main component**
final	cement industry	production of **clinker** as base material for **cement products**
final	ceramic industry	production of **ceramic products** like e.g. fireclay, fireclay bricks, bricks, tiles, clinker bricks, furnace lining, hot-face etc.
final	concrete production	production of **concrete** or **concrete products**
final	road construction and defined construction purposes	to use **fractions** under **'defined quality classes**' as road construction material or for other defined construction purposes (e.g. draining layers), see e.g. **technical standards** for the **material** applied (e.g. standards for certified recycling construction materials)
final	other construction purposes	to use fractions for - **unspecified construction material** for dams, for fills and filling of shafts - as **coverage material** for **landfill sites** - unspecified construction material for **driveway construction** at **landfill sites**
final	backfilling	to use fractions for - **reclamation purposes** in **excavated areas** (including **filling mines**) - **engineering purposes** in **landscaping**
final	plastics recycling	* to **use** plastics fractions for the production of **plastics products** * to **produce** e.g. extruded **granulates** ('defined quality classes', 'products') for the **production** industry of **plastics products** - to be used at any location for production of plastics products

i or f	technology used	remarks - technologies used
final	production of other products of/with plastics	to **use** plastics fractions for the production of **other** = mixed **products,** e.g. multilayer or mixed products
final	synthesis gas production	production of chemical **monomers** or **polymers** for **products**
final	particle board production	only to be used for **wood** being used as **wood feedstock**
final	paper/cardboard production	only to be used for **paper/cardboard** being used as **paper/cardboard feedstock**
final	co-incineration - with ER	**co-incineration** in a plant like e.g. cement kiln, particle board production (oven), paper plant (oven); other **fuel substituted** and/or **energy generated**
final	municipal waste incineration	**municipal waste incineration** plant, see '**purpose of the plant'** waste incineration = no fuel substitution to be calculated, below or no approval on meeting criteria on high energy efficiency - see Directive on waste DIRECTIVE 2008/98/EC
final	municipal waste incineration - high energy efficiency	**municipal waste incineration** plant **high energy efficiency** - see Directive on waste DIRECTIVE 2008/98/EC
final	hazardous waste incineration	**hazardous waste incineration** plant, see '**purpose of the plant'** waste incineration = no substitution
final	municipal waste incineration - special use	e.g. **special oven technology**, definite waste fractions, definite injection facilities etc. used for pre-heating the plant and/or to adjust temperature conditions or similar, definitely substitution of oil or gas
final	hazardous waste incineration - special use	e.g. glass fractions used for **'oven protection' / 'slag production'**, e.g. definite waste fractions, comparable (otherwise to be bought) amount as other slag forming component
final	landfill	municipal or common **landfills**
final	special landfill	**special landfills** like e.g. landfill sites for hazardous wastes, special sectors or underground landfills
final	battery recycling	e.g. 'wet'-chemical or smelting **processes** for the '**final' treatment** of **batteries**
final	production of 'new oil'	**cracking** of oil to achieve oil to be **used as 'oil'**
final	production of oil binding material	**production** of **oil binding material** e.g. from PU foam
final	(H)CFC splitting to products	**(H)CFC splitting** and production of **F-, Cl-**fractions for **use as products** (e.g. HCl, HF, Cl- or F-salts)
final	(H)CFC destruction	**(H)CFC-destruction** process, F-, Cl- and salt fractions for disposal
final	chemical / physical treatment as disposal process	**chemical / physical treatment** of fractions as **disposal process** like e.g. neutralisation of acids or bases
final	Hg distillation - final	**distillation plants** for **mercury** to achieve defined quality classes for the use of mercury in industry

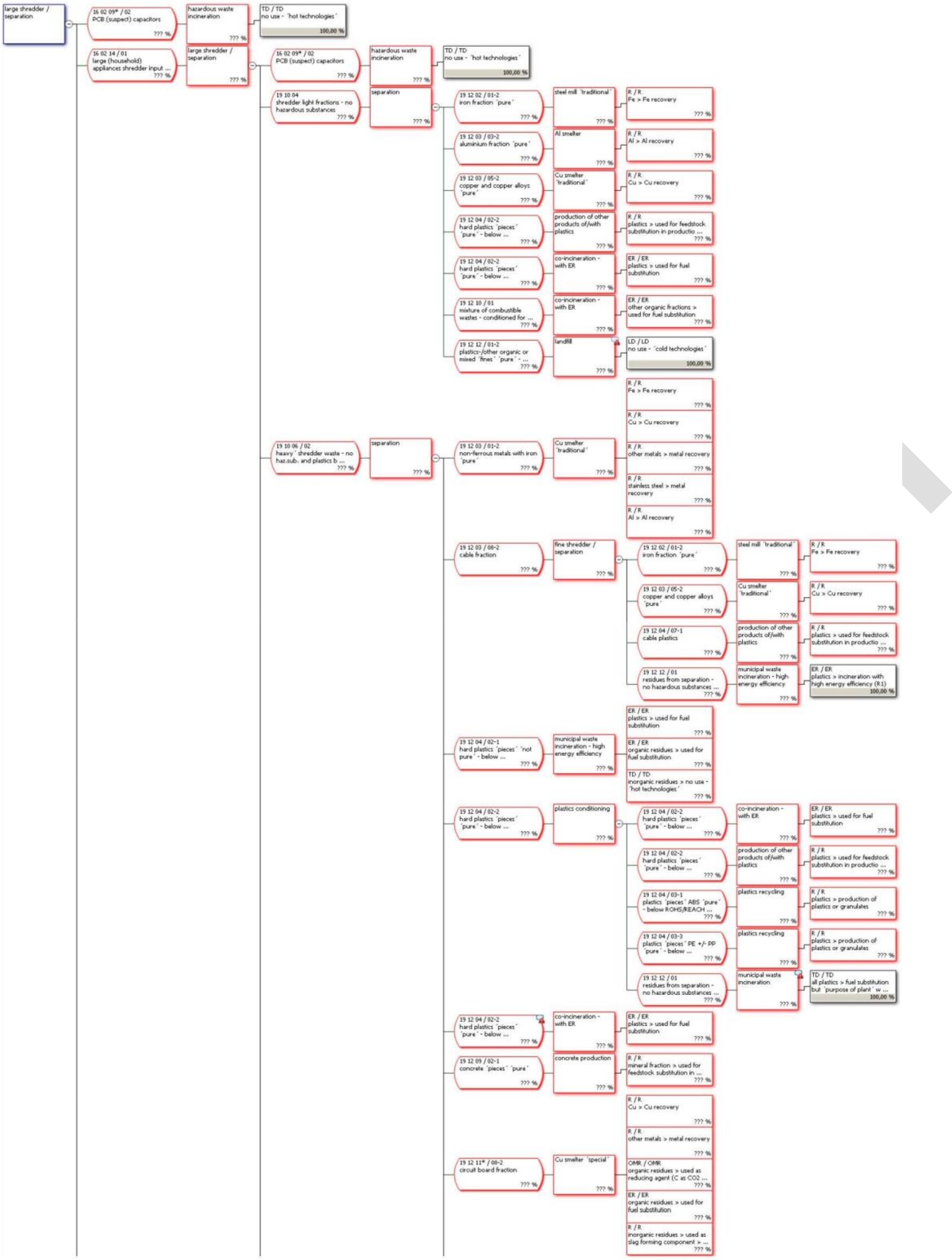
Annex 4: Classification of the target use of components in example technologies – WF-RepTool (as recycling, other material recovery, energy recovery)

Table 33: Classification of the target use of components in example technologies – WF-RepTool [126]

component / composition	further split	use in final technology	examples final process / technology & remarks	WF-class. 'new' WEEE Dir. 2012 model 2
Fe / stainless steel	Fe	Fe > Fe recovery	steel mill	R
		Fe > used as reducing agent > Fe to slag > slag as by-product or as defined product for use	Cu smelter - slag as by-product or defined product for use *(to be approved)*	R
		Fe > used as reducing agent > Fe to slag > slag not as by-product or as defined product for use	Cu smelter - slag not as by-product or defined product for use *[consider: Fe serves for an useful purpose by replacing other materials & fulfils a particular function (recovery definition)]*	OMR
		Fe > other use	info on technology	
	SS	stainless steel > metal recovery	stainless steel works	R
		stainless steel > used as reducing agent > stainless steel to slag > slag as by-product or as defined product for use	Cu smelter - slag as by-product or as defined product for use *(to be approved)*	R
		stainless steel > used as reducing agent > stainless steel to slag > slag not as by-product or as defined product for use	Cu smelter - slag not as by-product or as defined product for use *[consider: stainless steel serves for an useful purpose by replacing other materials & fulfils a particular function (recovery definition)]*	OMR
		stainless steel > other use	info on technology	
	Fe/SS	Fe / stainless steel > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		Fe / stainless steel > no use - 'cold technologies'	landfill	LD
Cu	Cu	Cu > Cu recovery	Cu smelter	R
		Cu > used as alloy material	Al smelter	R
		Cu > other use	info on technology	
		Cu > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		Cu > no use - 'cold technologies'	landfill	LD
Al	Al	Al > Al recovery	Al smelter	R
		Al > will burn off = no use	Cu smelter (see quality criteria to limit Al, see no compensation for Al)	TD
		Al > used as reducing agent > Al-oxides in slag as by-product or as defined product for use	steel mill (see quality criteria) - slag as by-product or as defined product for use *(to be approved)*	R
		Al > used as reducing agent > Al-oxides to slag > > slag not as by-product or as defined product for use	steel mill - slag not as by-product or as defined product for use *[consider: Al serves for an useful purpose by replacing other materials & fulfils a particular function (recovery definition)]*	OMR
		Al > other use	info on technology	
		Al > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		Al > no use - 'cold technologies'	landfill	LD
other metals	Pb	Pb > Pb recovery	Pb smelter Cu smelter (internal or external Pb recovery from filter material)	R
		Pb > other use	info on technology	
		Pb > no use	Pb smelter - share of Pb to slag being landfilled	LD
	Hg	Hg > Hg recovery	Hg distillation - final battery recycling with Hg separation step	R
		Hg > immobilisation	Cu smelter with Hg immobilisation step but next steps unclear	LD
		Hg > other use	info on technology	
	other metals	other metals > metal recovery	other metal smelters Cu smelter (other metals recovery direct or from filter material)	R
		other metals > used as alloy material	Cu smelter (see quality criteria) steel mill (see quality criteria) stainless steel works (see quality criteria) Al smelter (see quality criteria)	R
		other metals > used as reducing agent > metal to slag > slag as by-product or as defined product for use	Cu smelter - slag as by-product or as defined product for use *(to be approved)* steel mill - slag as by-product or as defined product for use *(to be approved)*	R
		other metals > used as reducing agent > metal to slag > slag not as by-product or as defined product for use	Cu smelter - slag not as by-product or as defined product for use steel mill - slag not as by-product or as defined product for use stainless steel works - slag not as by-product or as defined product for use *[consider: other metals serve for an useful purpose by replacing other materials & fulfil a particular function (recovery definition)]*	OMR
	all other metals	all other metals > other use	info on technology	
		all other metals > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		all other metals > no use - 'cold technologies'	landfill	LD
	rare earths	rare earths > rare earths recovery	final processes for rare earths	R
		rare earths > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		rare earths > no use - 'cold technologies'	landfill	LD

component / composition	further split	use in final technology	examples final process / technology & remarks	WF-class. 'new' WEEE Dir. 2012 model 2
plastics	plastics	plastics > production of plastics or granulates	plastics recycling	R
		plastics > used for feedstock substitution in production of other products of/with plastics	production of other products of/with plastics	R
		plastics > production of monomers or polymers for products	synthesis gas production	R
		plastics > used as reducing agent (C as CO2 emissions)	Cu smelter 'special' *(to be approved - e.g. by research studies)* steel mill 'special' *(to be approved - e.g. by research studies)* *examples:* ** add [consider .... (recovery definition)]*	OMR
		plastics > used for fuel substitution	Cu smelter 'special' *(to be approved - e.g. by research studies)* steel mill 'special' *(to be approved - e.g. by research studies)* co-incineration with ER municipal waste incineration - special use *(e.g. to heat up plant) (to be approved)* hazardous waste incineration - special use *(e.g. to heat up plant) (to be approved)*	ER
		plastics > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		plastics > no definite use in smelter	Cu smelter 'traditional' steel mill 'traditional'	TD
		plastics > other use	info on technology	
	PU	PU > used as oil binding material	production of oil binding material	R
		PU > used for feedstock substitution in production of other products of/with plastics	production of other products of/with plastics	R
		PU > production of monomers or polymers for products	synthesis gas production	R
		PU > used for fuel substitution	co-incineration with ER	ER
		PU > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		PU > other use	info on technology	
	all plastics	all plastics > fuel substitution but 'purpose of plant' waste incineration	municipal waste incineration hazardous waste incineration	TD
		all plastics > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		all plastics > no use - 'cold technologies'	landfill	LD
other organic fractions	wood	wood > used as raw material in particle board production	particle board production *[consider: wood used for product; if 'to oven', see used for fuel substitution]*	R
		wood > used for fuel substitution	co-incineration with ER - e.g. also particle board production plant (oven)	ER
		wood > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		wood > other use	info on technology	
	paper/cardboard	paper/cardboard > used as raw material in paper/cardboard recycling	paper/cardboard recycling *[consider: paper/cardboard used for product; if 'to oven', see used for fuel substitution]*	R
		paper/cardboard > used for fuel substitution	co-incineration with ER - e.g. also paper plant (oven)	ER
		paper/cardboard > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		paper/cardboard > other use	info on technology	
	oil fraction	oil fraction > used as raw material in production of 'new oil'	production of 'new oil'	R
		oil fraction > used for fuel substitution	co-incineration with ER	ER
		oil fraction > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		oil fraction > other use	info on technology	
	(H)(C)FC fractions	(H)(C)FC fractions > production of monomers for products and/or products	CFC splitting to products *(use only for shares of CFC's going to products!, for 'wastes' use other option/s)*	R
		(H)(C)FC fractions > destruction	hazardous waste incineration CFC destruction	TD
		(H)(C)FC fractions > other use	info on technology	
	other organic fractions	other organic fractions > used for fuel substitution	co-incineration with ER	ER
		other organic fractions > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		other organic fractions > other use	info on technology	
	all other organic fractions	all other organic fractions > fuel substitution but 'purpose of plant' waste incineration	municipal waste incineration hazardous waste incineration	TD
		all other organic fractions > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		all other organic fractions > no use - 'cold technologies'	landfill	LD
organic residues	organic residues	organic residues > production of monomers or polymers for products	synthesis gas production	R
		organic residues > used as reducing agent (C as CO2 emissions)	Cu smelter 'special' *(to be approved - e.g. by research studies)* *[consider: organic residues serve for an useful purpose by replacing other materials & fulfil a particular function (recovery definition)]*	OMR
		organic residues > used for fuel substitution	Cu smelter 'special' *(to be approved - e.g. by research studies)* co-incineration with ER *(to be approved - acceptance of mixed fractions)*	ER
		organic residues > incineration with high energy efficiency (R1)	municipal waste incineration - high energy efficiency (R1) *(to be approved)*	ER
		organic residues > other use	info on technology	
		organic residues > fuel substitution but 'purpose of plant' waste incineration	municipal waste incineration hazardous waste incineration	TD
		organic residues > no definite use in smelter	Cu smelter 'traditional' steel mill 'traditional'	TD
		organic residues > no use - 'hot technologies'	municipal waste incineration hazardous waste incineration	TD
		organic residues > no use - 'cold technologies'	landfill	LD

Annex 5: EoL scenarios for WEEE developed by Renate Gabriel by using the WF-RepTool (section 3.2.1)



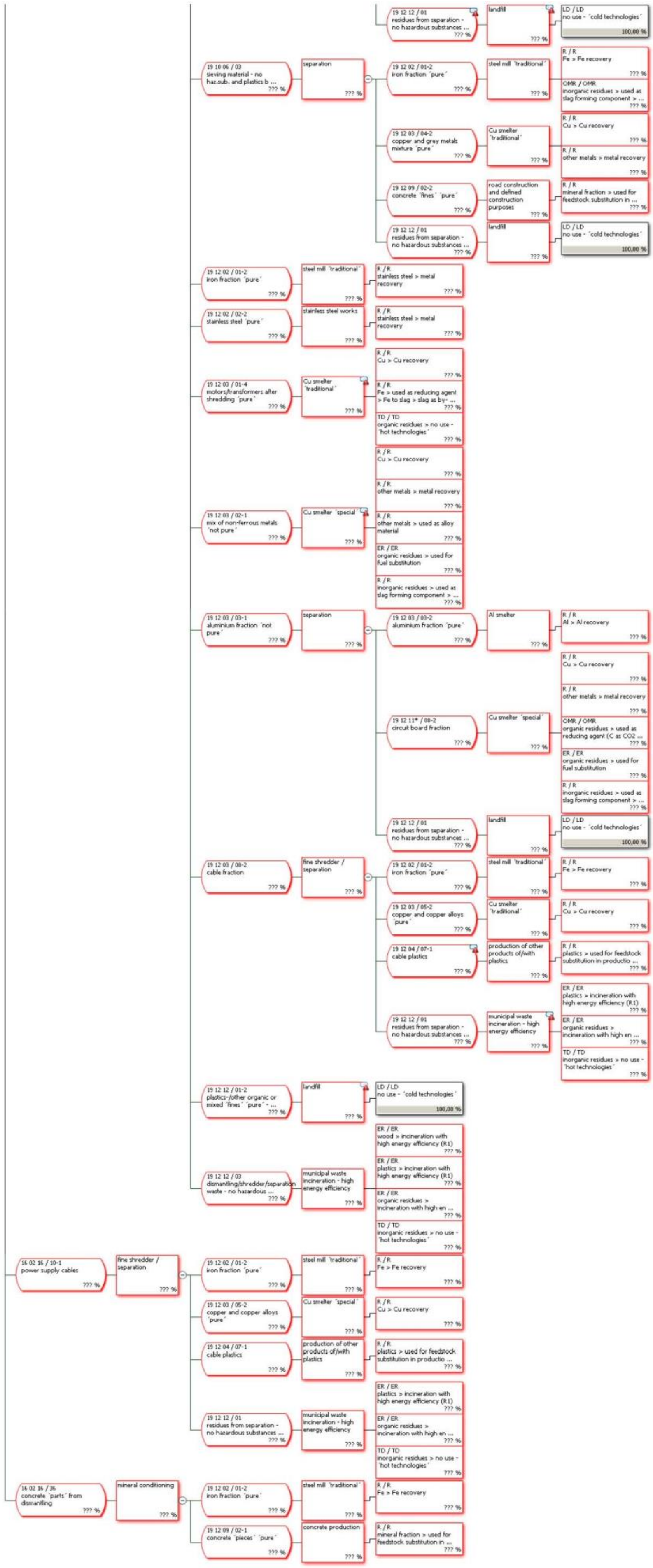
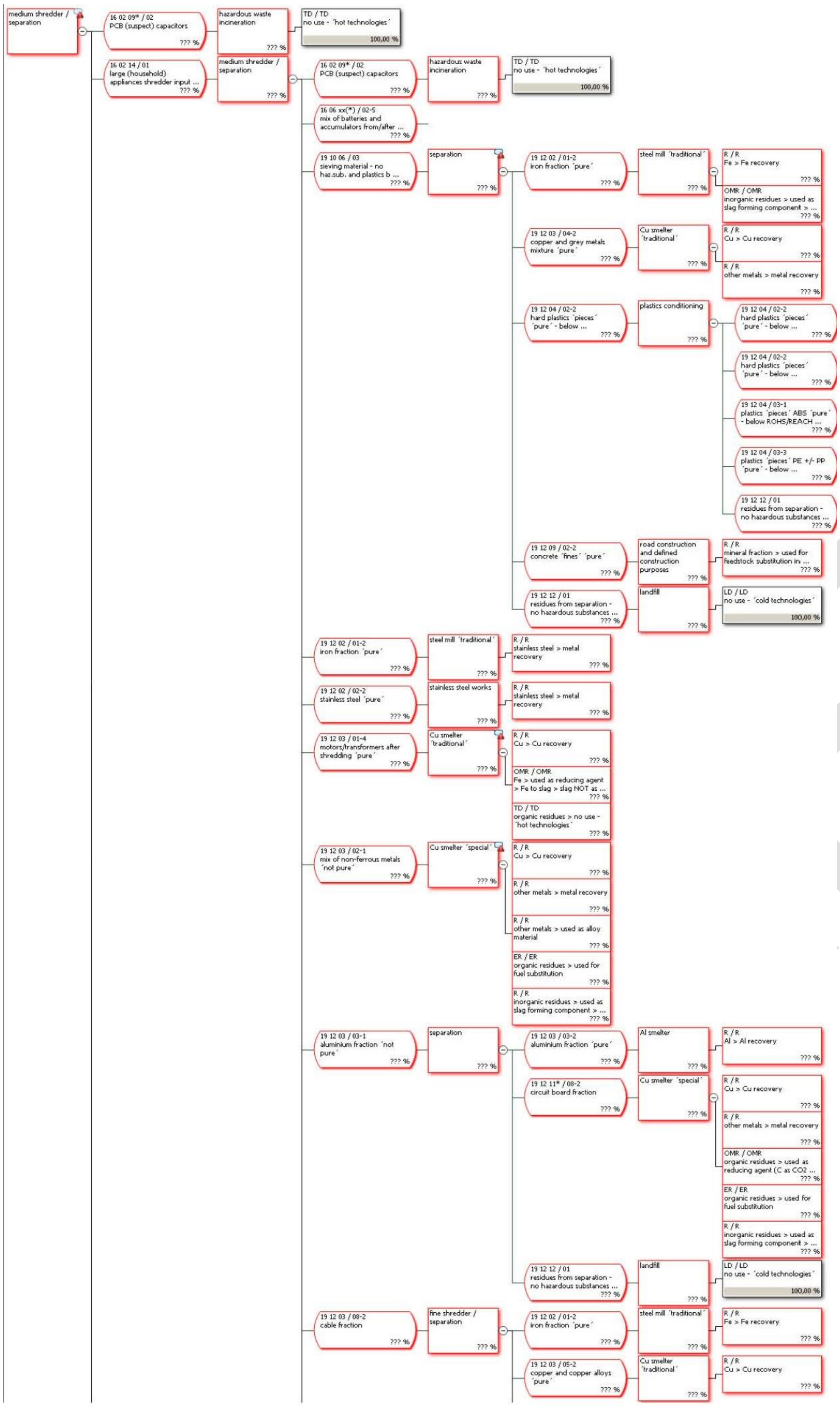


Figure 14: End-of-life scenario for large household appliances (case regular car large shredder / separation) [72]


medium shredder / separation
16 02 09* / 02
PCB (suspect) capacitors
hazardous waste incineration
TD / TD
no use - 'hot technologies'
100,00 %
16 02 14 / 01
large (household) appliances shredder input ...
medium shredder / separation
16 02 09* / 02
PCB (suspect) capacitors
hazardous waste incineration
TD / TD
no use - 'hot technologies'
100,00 %
16 06 xx(*) / 02-5
mix of batteries and accumulators from/after ...
19 10 06 / 03
sieving material - no haz.sub. and plastics b ...
separation
19 12 02 / 01-2
iron fraction 'pure'
steel mill 'traditional'
R / R
Fe > Fe recovery
OMR / OMR
inorganic residues > used as slag forming component > ...
19 12 03 / 04-2
copper and grey metals mixture 'pure'
Cu smelter 'traditional'
R / R
Cu > Cu recovery
R / R
other metals > metal recovery
19 12 04 / 02-2
hard plastics 'pieces' 'pure' - below ...
plastics conditioning
19 12 04 / 02-2
hard plastics 'pieces' 'pure' - below ...
19 12 04 / 02-2
hard plastics 'pieces' 'pure' - below ...
19 12 04 / 03-1
plastics 'pieces' ABS 'pure' - below ROHS/REACH ...
19 12 04 / 03-3
plastics 'pieces' PE +/- PP 'pure' - below ...
19 12 12 / 01
residues from separation - no hazardous substances ...
19 12 09 / 02-2
concrete 'fines' 'pure'
road construction and defined construction purposes
R / R
mineral fraction > used for feedstock substitution in ...
19 12 12 / 01
residues from separation - no hazardous substances ...
landfill
LD / LD
no use - 'cold technologies'
100,00 %
19 12 02 / 01-2
iron fraction 'pure'
steel mill 'traditional'
R / R
stainless steel > metal recovery
19 12 02 / 02-2
stainless steel 'pure'
stainless steel works
R / R
stainless steel > metal recovery
19 12 03 / 01-4
motors/transformers after shredding 'pure'
Cu smelter 'traditional'
R / R
Cu > Cu recovery
OMR / OMR
Fe > used as reducing agent > Fe to slag > slag NOT as ...
TD / TD
organic residues > no use - 'hot technologies'
19 12 03 / 02-1
mix of non-ferrous metals 'not pure'
Cu smelter 'special'
R / R
Cu > Cu recovery
R / R
other metals > metal recovery
R / R
other metals > used as alloy material
ER / ER
organic residues > used for fuel substitution
R / R
inorganic residues > used as slag forming component > ...
19 12 03 / 03-1
aluminium fraction 'not pure'
separation
19 12 03 / 03-2
aluminium fraction 'pure'
Al smelter
R / R
Al > Al recovery
19 12 11* / 08-2
circuit board fraction
Cu smelter 'special'
R / R
Cu > Cu recovery
R / R
other metals > metal recovery
OMR / OMR
organic residues > used as reducing agent (C as CO2 ...
ER / ER
organic residues > used for fuel substitution
R / R
inorganic residues > used as slag forming component > ...
19 12 12 / 01
residues from separation - no hazardous substances ...
landfill
LD / LD
no use - 'cold technologies'
100,00 %
19 12 03 / 08-2
cable fraction
fine shredder / separation
19 12 02 / 01-2
iron fraction 'pure'
steel mill 'traditional'
R / R
Fe > Fe recovery
19 12 03 / 05-2
copper and copper alloys 'pure'
Cu smelter 'traditional'
R / R
Cu > Cu recovery

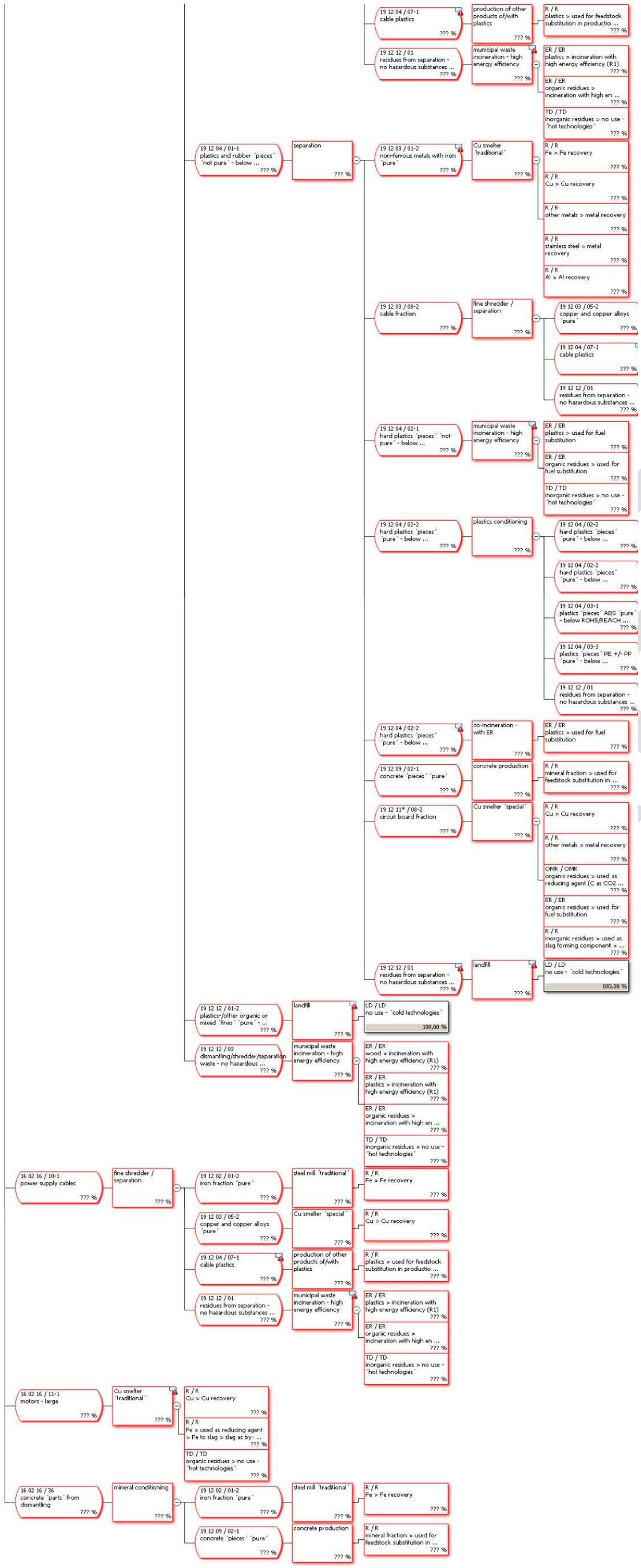
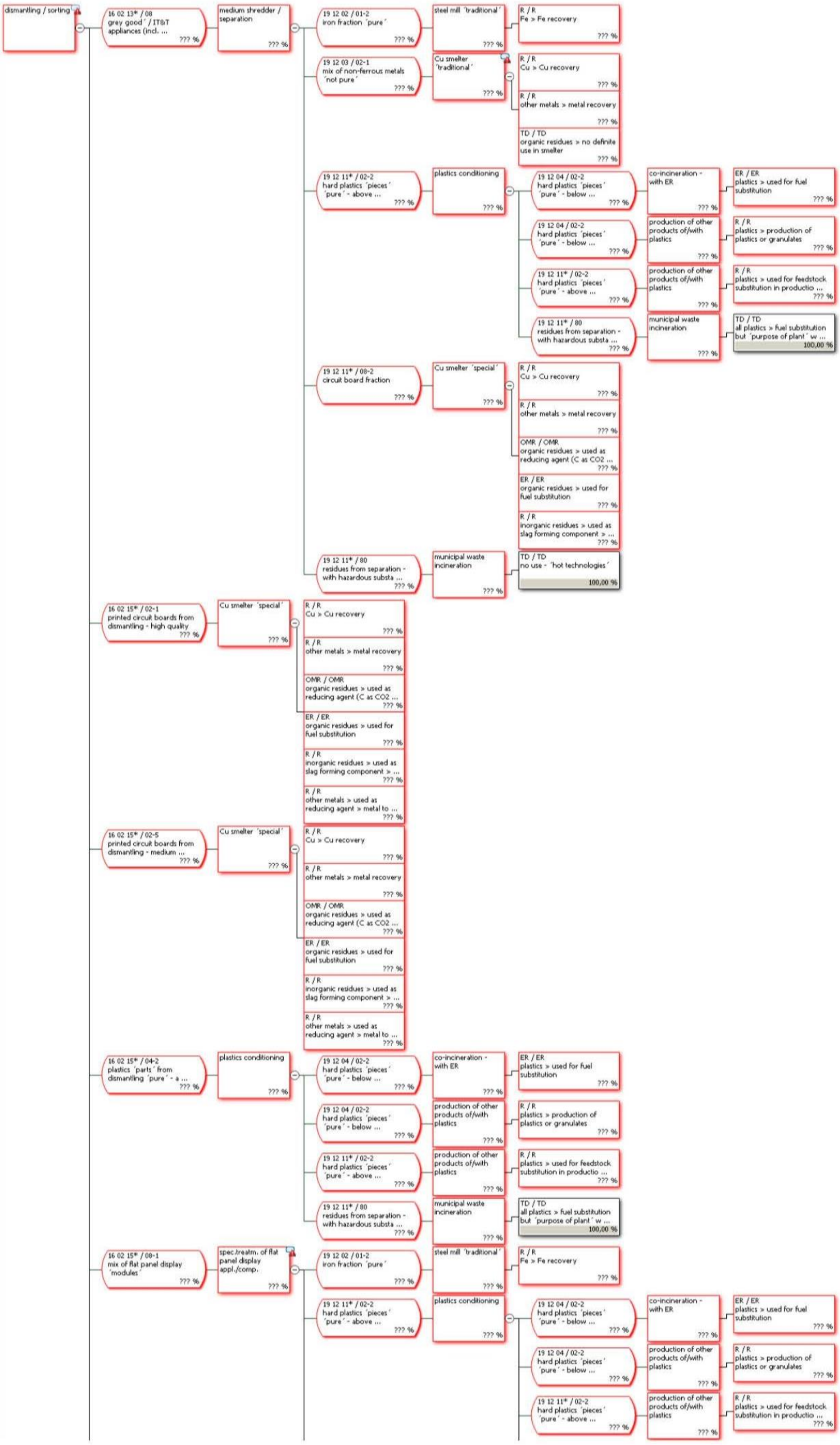


Figure 15: End-of-life scenario for large household appliances (case medium shredder / separation) [72]


dismantling / sorting
16 02 13* / 08 grey good´ / IT&T appliances (incl. ... ??? %
medium shredder / separation ??? %
19 12 02 / 01-2 iron fraction ´pure´ ??? %
steel mill ´traditional´ ??? %
R / R Fe > Fe recovery ??? %
19 12 03 / 02-1 mix of non-ferrous metals ´not pure´ ??? %
Cu smelter ´traditional´ ??? %
R / R Cu > Cu recovery ??? %
R / R other metals > metal recovery ??? %
TD / TD organic residues > no definite use in smelter ??? %
19 12 11* / 02-2 hard plastics ´pieces´ ´pure´ - above ... ??? %
plastics conditioning ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
co-incineration - with ER ??? %
ER / ER plastics > used for fuel substitution ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
production of other products of/with plastics ??? %
R / R plastics > production of plastics or granulates ??? %
19 12 11* / 02-2 hard plastics ´pieces´ ´pure´ - above ... ??? %
production of other products of/with plastics ??? %
R / R plastics > used for feedstock substitution in productio ... ??? %
19 12 11* / 80 residues from separation - with hazardous substa ... ??? %
municipal waste incineration ??? %
TD / TD all plastics > fuel substitution but ´purpose of plant´ w ... 100,00 %
19 12 11* / 08-2 circuit board fraction ??? %
Cu smelter ´special´ ??? %
R / R Cu > Cu recovery ??? %
R / R other metals > metal recovery ??? %
OMR / OMR organic residues > used as reducing agent (C as CO2 ... ??? %
ER / ER organic residues > used for fuel substitution ??? %
R / R inorganic residues > used as slag forming component > ... ??? %
19 12 11* / 80 residues from separation - with hazardous substa ... ??? %
municipal waste incineration ??? %
TD / TD no use - ´hot technologies´ 100,00 %
16 02 15* / 02-1 printed circuit boards from dismantling - high quality ??? %
Cu smelter ´special´ ??? %
R / R Cu > Cu recovery ??? %
R / R other metals > metal recovery ??? %
OMR / OMR organic residues > used as reducing agent (C as CO2 ... ??? %
ER / ER organic residues > used for fuel substitution ??? %
R / R inorganic residues > used as slag forming component > ... ??? %
R / R other metals > used as reducing agent > metal to ... ??? %
16 02 15* / 02-5 printed circuit boards from dismantling - medium ... ??? %
Cu smelter ´special´ ??? %
R / R Cu > Cu recovery ??? %
R / R other metals > metal recovery ??? %
OMR / OMR organic residues > used as reducing agent (C as CO2 ... ??? %
ER / ER organic residues > used for fuel substitution ??? %
R / R inorganic residues > used as slag forming component > ... ??? %
R / R other metals > used as reducing agent > metal to ... ??? %
16 02 15* / 04-2 plastics ´parts´ from dismantling ´pure´ - a ... ??? %
plastics conditioning ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
co-incineration - with ER ??? %
ER / ER plastics > used for fuel substitution ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
production of other products of/with plastics ??? %
R / R plastics > production of plastics or granulates ??? %
19 12 11* / 02-2 hard plastics ´pieces´ ´pure´ - above ... ??? %
production of other products of/with plastics ??? %
R / R plastics > used for feedstock substitution in productio ... ??? %
19 12 11* / 80 residues from separation - with hazardous substa ... ??? %
municipal waste incineration ??? %
TD / TD all plastics > fuel substitution but ´purpose of plant´ w ... 100,00 %
16 02 15* / 08-1 mix of flat panel display ´modules´ ??? %
spec.treatm. of flat panel display appl./comp. ??? %
19 12 02 / 01-2 iron fraction ´pure´ ??? %
steel mill ´traditional´ ??? %
R / R Fe > Fe recovery ??? %
19 12 11* / 02-2 hard plastics ´pieces´ ´pure´ - above ... ??? %
plastics conditioning ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
co-incineration - with ER ??? %
ER / ER plastics > used for fuel substitution ??? %
19 12 04 / 02-2 hard plastics ´pieces´ ´pure´ - below ... ??? %
production of other products of/with plastics ??? %
R / R plastics > production of plastics or granulates ??? %
19 12 11* / 02-2 hard plastics ´pieces´ ´pure´ - above ... ??? %
production of other products of/with plastics ??? %
R / R plastics > used for feedstock substitution in productio ... ??? %

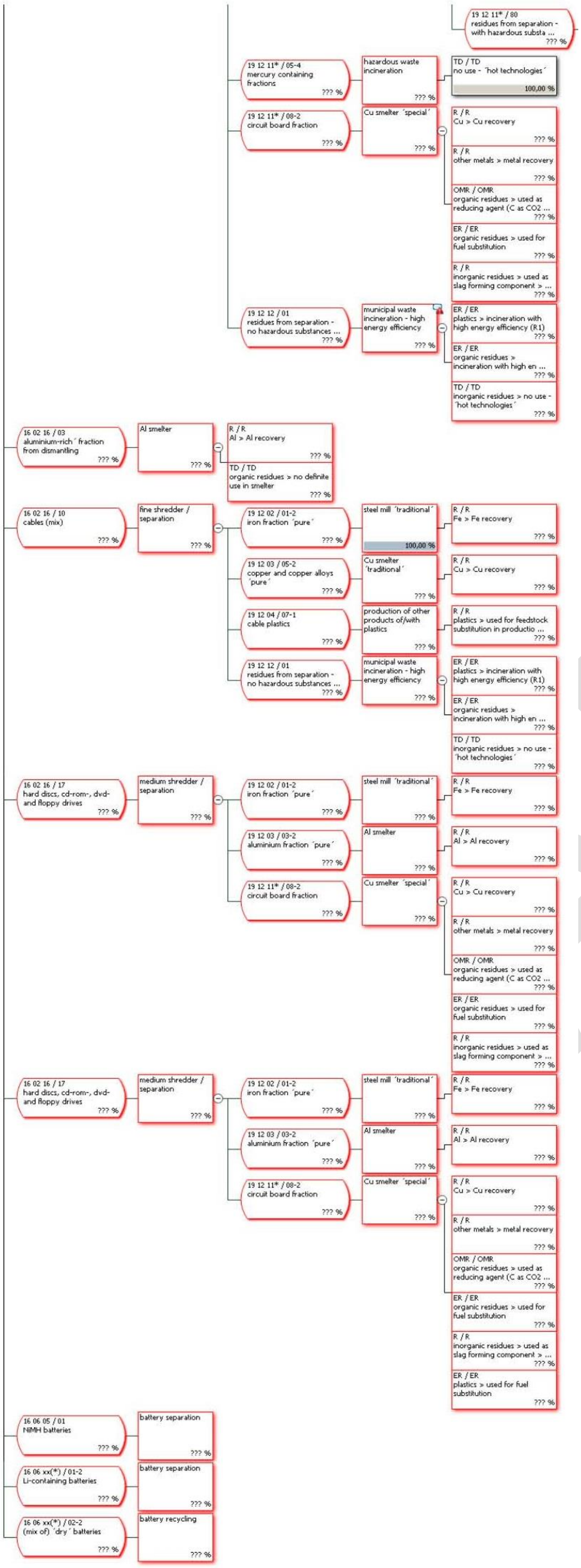


Figure 16: End-of-life scenario for flat panel display appliances (case/example medium depth dismantling) [72]

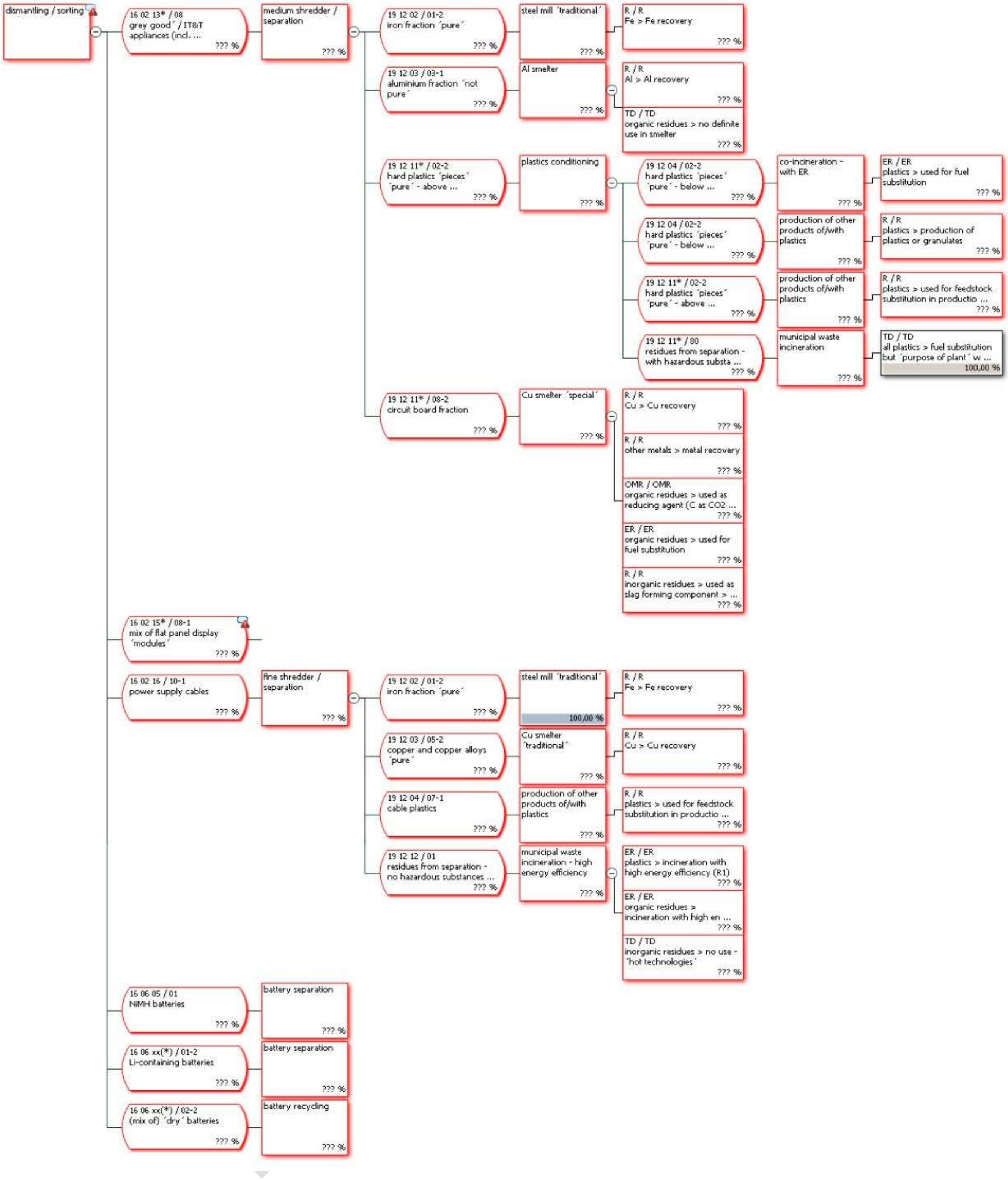


Figure 17: End-of-life scenario for flat panel display appliances (case/example laptop bodies to smelters) [72]

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