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Integration of resource efficiency and waste management criteria in the implementing measures under the Ecodesign Directive

In-depth analysis of the measurement and verification approaches, identification of the possible gaps and recommendations

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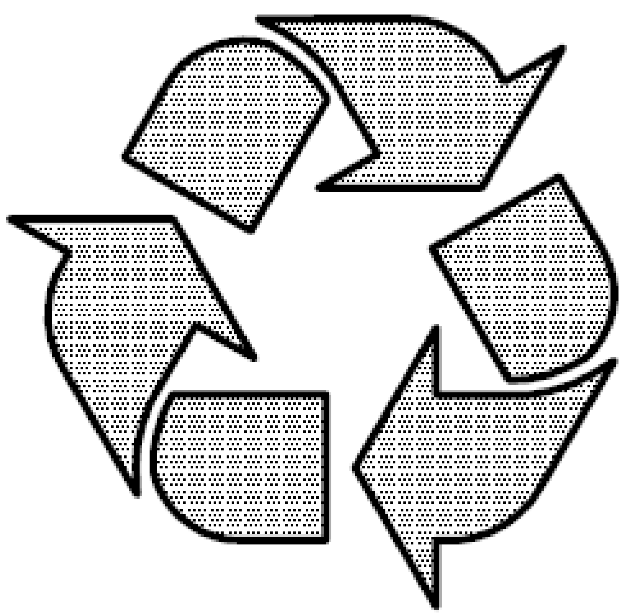

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Table of contents

Executive Summary

The present Deliverable develops new methodologies for the measurement and the verification of the following parameters for use in Ecodesign policies:

- Reusability/Recyclability/Recoverability (*RRR*);
- Recycled content;
- Use of priority resources;
- Use of hazardous substances.

Note that these methodologies will be further developed in a subsequent project in order to define concise technical provisions suitable for their potential use in the Ecodesign policies.

Structure of the methodologies

The methodologies are based on the calculation of one (or more) indices for each of the above parameters. The indices can be applied at the design stage.

The indices have a 'modular' structure. This means that they are calculated as product of different sub-indices. The modularity of the indices allows including or excluding some of the sub-indices without compromising the methodology itself. Furthermore, new sub-indices can be added in future, reflecting additional aspects that have not been investigated at this stage. Analogously, some indexes can be modified or removed on the basis of the expected targets of the decision-makers, effectiveness, and other considerations.

A summary of the developed indices is provided in the next sections.

Verification procedures

Verification procedures have been elaborated for each index and sub-index.

The verification is based on self-declarations supported by technical documentation available before the product is put into the market and provided on request (e.g. to be checked by a competent body).

The declarations could be verified for example by a Market Surveillance Authority that would check the truthfulness of provided information (e.g. BOM, 'disassembly scheme') and successively would follow the calculation of the indices done by the manufacturer in specific 'calculation data sheet'.

The Bill of Materials

The compilation of the Bill of Materials (BOM) is the first step of the assessment of all the project's parameters. The BOM gathers information about the product structure and composition. A scheme of the BOM and a procedure for its drafting is presented.

Methodology for the measurement of product's Reusability/Recyclability/Recoverability

Reusability, Recyclability, Recoverability (*RRR*) are '*potentials*' of the product[2].

According to the outcomes of the scientific and legislative survey (developed in Deliverable 1), three indices for *RRR* have been defined. These simple indices are structured as the 'ratio' (percentage) between the potential reusable/recyclable/recoverable mass of a product and its overall mass. The ratios are calculated by means of calculation spreadsheets that combine the information from the BOM with additional information concerning[3]:

- Disassembly of the product,
- Physical/chemical degradation of the materials that constitute the product, and
- Contaminations that occur among different materials that could compromise their reuse, recycle or recovery.

The proposed indices have a general structure and are generally applicable to a wide range of product categories.

Note that these 'mass ratio' indices are not differentiates by materials and they do not capture the substantially different environmental benefit of the reuse/recycling/recovery of different materials. More effective indices can be derived by integration of such a differentiation via a prioritisation/valorisation of resources (see next sections).

Methodology for the prioritisation of the resources

According to the scope of the project, the attention has been focused on the *RRR* and the potential benefits related to the reuse/recycling/recovery of the materials as a key issue for their prioritisation.

The benefits can be calculated on the basis of life cycle data about the production of primary and secondary materials. On such purpose, a '*differential index*' has been defined as the difference between the environmental impact to produce one unit of primary material and that to produce the same quantity from end-of-life products.

The differential index can be calculated referring to any life cycle impact category. In the present Deliverable the calculations have been illustrated on the 'Global Warming Potential' and the 'Primary Energy consumption' impact categories.

Resource prioritisation and indices for the Reusability/Recyclability/Recoverability

Data concerning the 'prioritised' materials have been successively integrated in the methodologies for the measurement of *RRR*. A new set of indices is derived. The new indices (called "Reusability/Recyclability/Recoverability Benefit Ratios' indices) allow:

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[2] Note that RRR potentials largely differ from the effective reuse/recycle/recovery of the product.

[3]. Some exemplary tables for the calculation of the disassemblability, contamination and degradation have been provided. However, these tables are only illustrative of the proposed approach and they should be further refined before to be suitable for the use into EU policies.

- Defining a hierarchy among the benefits related to the different End-of-life treatments of the analysed product;
- Identifying the product's components with the highest potential environmental benefits if reused/recycled/recovered.

The new set of indices represents therefore a progress '*beyond the current state of art*', developed on the basis of newer insights of the technical/scientific literature and particularly focused on the life cycle thinking and assessment. In particular, the new indices represent a progress compared to the basic 'mass based' indices because they embody the potential benefits that could be achieved by reusing/recycling/recovering the product's component.

<u>Methodology for the measurement of the product's recycled content</u>

Differently from *RRR*, the recycled content is a physical 'property' of the product, related to its composition and manufacturing history including the entire supply-chain.

Unfortunately, the recycled content cannot be directly measured on the final product but it can be only indirectly derived via collecting supply-chain information. Various international standards or environmental certification schemes have already developed procedures for the "measurement" (i.e. approximation) of the recycled content.

A Recycled content index is introduced in this Deliverable. The index is calculated by means of spreadsheets that combine the information from the BOM with additional information concerning the recycled content of each component and material. This information has to be provided by the manufacturer and ultimately his suppliers.

The calculation of the Recycled content index has been illustrated with some exemplary tables and figures.

<u>Case-study application</u>

The above described methodologies have been applied to an illustrative case-study: an internal Hard Disk Drive (HDD) for desktop computer.

RRR mass ratios have been initially calculated. Successively potential benefits derived from the *RRR* of the product have been estimated. Finally, the new '*RRR* Benefit Ratio' indices have been calculated and compared to the initial 'mass *RRR*' indices.

It is noted that the *RRR* Benefit Ratio indices allow a more consistent analysis of the product compared to mass indices. For example, a material that is not-relevant in terms of mass could be very relevant in terms of environmental impacts or potential environmental benefits when recycled (e.g. gold in the printed circuit board). Furthermore, the '*RRR* Benefit Ratio' indices can be used to identify critical components of the product (i.e. those that can grant the largest benefits if reused/recycled/recovered). The *RRR* Benefit Ratio indices could represent a support for the development of potential Ecodesign requirements.

The case-study analysis also calculated 'recycled content' of the HDD on the basis of estimated average data about the recycled content of materials.

It is noted that the scope of requirements on the recycled content is to push manufacturers to use secondary materials that otherwise would have been differently treated (e.g. landfilled) because they are not ‘attractive’ for the recycling due to their low market value or the low market demand. Potential target materials for “recycled content” requirements can be, for example, materials that are generally not recycled because of some barriers (e.g. economic costs or limited consumer acceptance).

A methodology for the assessment of the use of hazardous substances

A methodology for the assessment of the use of hazardous substances in products is presented. The methodology is based on a multi-criteria environmental analysis that aims at assessing how the content of hazardous substances can affect the ecoprofile of a case-study product. The analysis goes beyond the pure content of potential harmful substances but includes their impacts over the life cycle as well as effects on other product characteristics including use, performance/efficiency, etc.

The methodology can be useful to identify ‘key’ components of the product that have the highest environmental impacts. Design requirements should focus on these ‘key’ components.

Identification of Ecodesign requirements

The final section of the Deliverable presents and discusses some potential Ecodesign requirements concerning the project’s parameters. The requirements have been built upon the previous methodological analysis and the case-study application. Each identified potential requirement includes also a description of the verification procedure.

All the discussed requirements are illustrative and the have to be considered as ‘prototypes’ potentially adaptable to different product categories.

Some requirements include minimum thresholds that have to be specifically set for each product category. Other potential requirements are instead declarative/descriptive. In general, the requirements are applicable to a wide range of product categories.

It is important to highlight that some of the Ecodesign requirements here discussed could potentially lead to design measures that worsen the product's overall environmental life cycle performance. For example, the reuse of some EuP’s components could cause higher energy consumption during the use phase.

In order to avoid potential ‘shifting of burden’ it is recommended the adoption of a life cycle check for the assessment of thresholds Ecodesign requirements applied to the specific product category.

Summary of the developed indices

The present section summarizes the main indices (and the related sub-indices) that have been developed and discussed in the present Deliverable. The summary makes reference to the formulas and the pages of the Deliverable where the indices have been introduced.

1. **Simple and combined indices for the measurement of the Reusability/Recyclability/Recoverability (*RRR*) potentials**

- '*Reusability Ratio*' (R_{Reuse}) [%] (Formula 1- page 41)
    - 'Potential reusable mass' (m_{reuse}) [kg] (Formula 6 - page 44)
        - 'Disassemblability' index (D) [%] (Formula 9 – page 48)
        - 'Material Degradation' index (M_D) [%] (Formula 13 – page 59)
- '*Recyclability Ratio*' ($R_{Recycle}$) [%] (Formula 2 – page 41)
    - 'Potential recyclable mass' ($m_{Recycle}$) [kg] (Formula 7 – page 44)
        - 'Disassemblability' index (D) [%] (Formula 9 – page 48)
        - 'Materials Contamination index for recyclability' (C_1) and 'Absence of Contamination index for recyclability' (C_1') [%] (Table 11 – page 56)
        - 'Material Recyclability' (M_R) [%] (Formula 14 – page 62)
- *Indices for Recoverability*
    - 'Energy Recoverability Ratio' ($ER_{Recovery}$) [%] (Formula 3 – page 42)
        - 'Potential energetically recoverable mass' ($m_{E\text{-}recovery}$) [kg] (Formula 8 – page 44)
            - 'Disassemblability' index (D) [%] (Formula 9 – page 48)
            - 'Contamination index for energy recovery' (C_2) and 'Absence of Contamination index for energy recovery' (C_2') [%] (Table 12 – page 57)
    - 'Recoverability Ratio' ($R_{Recovery}$) [%] (Formula 4 – page 42)
        - 'Potential recyclable mass' ($m_{Recycle}$) [kg] (Formula 7 – page 44)
        - 'Potential energetically recoverable mass' ($m_{E\text{-}recovery}$) [kg] (Formula 8- page 44)
- Combined 'Reusability/Recyclability' and 'Reusability/Recoverability' indices
    - 'Reusability/Recyclability' ($R_{ReuseRecycle}$) [%] (Formula 15 – page 70)
        - 'Potential reusable mass' (m_{reuse}) [kg] (Formula 6 - page 44)
        - 'Potential recyclable mass' ($m_{Recycle}$) [kg] (Formula 7 – page 44)
    - 'Reusability/Recoverability' ($R_{ReuseRecovery}$) [%] (Formula 16 – page 71)
        - 'Potential reusable mass' (m_{reuse}) [kg] (Formula 6 - page 44)
        - 'Potential recyclable mass' ($m_{Recycle}$) [kg] (Formula 7 – page 44)
        - 'Potential energetically recoverable mass' ($m_{E\text{-}recovery}$) [kg] (Formula 8 - page 44)

2. **Integration of resource prioritization and environmental benefits with indices for the measurement of RRR potentials**

- ‘*Reusability Benefit Ratio*’ ($R_{eusability,Benefit}$) [%] (Formula 27 – page 100)
    - ‘Disassemblability’ index (D) [%] (Formula 9 – page 48)
    - ‘Material Degradation’ index (M_D) [%] (Formula 13 – page 59)
    - ‘Impact related to the primary production’ ($I_{i,k}$) [kg CO_2eq./kg] (Table 19 – page 90)
- ‘*Recyclability Benefit Ratio*’ ($R_{ecyclability,Benefit}$) [%] (Formula 28 – page 101)
    - ‘Disassemblability’ index (D) [%] (Formula 9 – page 48)
    - ‘Materials Contamination index for recyclability’ (C_1) and ‘Absence of Contamination index for recyclability’ (C_1') [%] (Table 11 – page 56)
    - ‘Material Recyclability’ (M_R) [%] (Formula 14 – page 62)
    - ‘Differential Impact’ index (δ) [kg CO_2eq. /kg] (Formula 17 – page 85)
- ‘*Energy Recoverability Benefit Ratio*’ ($ERecoverability_{Benefit}$) [%] (Formula 29- page 102)
    - ‘Disassemblability’ index (D) [%] (Formula 9 – page 48)
    - ‘Contamination index for energy recovery’ (C_2) and ‘Absence of Contamination index for energy recovery’ (C_2') [%] (Table 12 – page 57)

3. **Recycled content of a material and of a product/component**

- ‘*Recycled content of a product/component*’ ($R_{Content}$) [%] (Formula 32- page 113)
    - ‘Material recycled content’ ($r_{Content}$) [kg] (Formula 31- page 112)
- ‘*Pre-consumers recycled content*’ ($R_{Content,PRE}$) [%] (Formula 33- page 115)
- ‘*Post-consumers recycled content*’ ($R_{Content,POST}$) [%] (Formula 34 – page 115)

4. **Impact assessment of the use of hazardous substances**

- Multi-criteria impact assessment (Table 41 – page **Error! Bookmark not defined.**)

Abbreviations

ABS – Acrylonitrile-butadiene styrene
AP - Acidification Potential
ADP – Abiotic Resource Depletion Potential
BOM – Bill of Materials
“C” index - Contamination index
CFL – Compact Fluorescent Lamp
“D” index - Disassembly index
EEE – Electrical and Electronic Equipment
ELCD - European Reference Life Cycle Database
EoL – End of Life
ELV – End-of Life of Vehicles
ERP – Energy Related Product (as defined by Directive 2009/125/EC)
EUP – Energy Using Products (as defined by Directive 2005/32/EC)
EP - Eutrophication Potential
FAETP - Freshwater Aquatic Ecotoxicity Potential
GWP - Global Warming Potential
HHV – Higher Heating Value
HTP - Human Toxicity Potential
ILCD – International Reference Life Cycle Data System
IM – Implementing Measures
ISO – International Organization for Standardization
JRC – European Commission’s Joint Research Centre
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LED – Light Emitting Diode
LHV - Lower Heating Value
LMF – Lumen Maintenance Factor
MEEUP - Methodology study for Eco-design of Energy-Using Products
MD - Material Degradation index
ODP - Ozone Layer Depletion Potential
PC - Polycarbonate
PE – Polyethylene
PEC – Primary Energy Consumption
PE-HD – Polyethylene high density (also as HDPE)
PE-LD - Polyethylene low density (also as LDPE)
PEC – Primary Energy Consumption
PET – Polyethylene Terephthalate
PP – Polypropylene
PS – Polystyrene
PS- E – Polystyrene expandable
POCP - Photochemical Ozone Creation Potential
PVC – Polyvinyl chloride
REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals (Regulation EC 1907/2006)
RoHS – Restriction of Hazardous Substances (as defined by Directive 2002/95/EC)
RRR – Recyclability, Reusability and Recoverability
SCP/SIP - Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan
SVHC – Substance of Very High Concern (as defined by REACH Regulation EC 1907/2006)
TETP - Terrestric Ecotoxicity Potential
WEEE – Waste Electrical and Electronic Equipment

Main Definitions

Assembly: A set of parts so assembled.

Bill Of Materials (BOM): document that synthesizes a detail of the product's composition.

Component: A constituent element of a system/product (synonym of part). It can be constituted by one or more different materials, and by other components assembled together (sub-assemblies).

Disassembly index 'D': it estimates the aptitude of the product's components to be separated and addressed to further EoL treatments.

Energy Recoverability: A product or its parts are 'energy recoverable' when they have an embodied energy content (feedstock) that can be potentially recovered after incineration. Energy Recoverability is an estimation of such potential.

Feedstock Energy: the heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value.

Global Warming Potential (GWP): is an index that has been introduced to assess the contribution of a greenhouse gas to the global warming and the climate changes impact. Characterization factors for greenhouse gases are calculated and updated by the Intergovernmental Panel on Climate Change.

Higher Heating Value (HHV) of a fuel is defined as the amount of heat released by a specified quantity once it is combusted (at the reference temperature), the products have returned to the environment temperature.

Life Cycle Assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Lower Heating Value (LHV): is the amount of heat released by combusting a specified quantity of fuel (at reference temperature) and returning the combustion products at the temperature of 150.

Lumen Maintenance Factor (LMF): it represents the proportion of light output of a lamp, compared with initial lumen output.

Materials' Contamination index '*C*': it estimates how much the presence of contaminants of the materials could potentially interfere with the product's reuse, recycle or recovery.

Material Degradation' index 'M_D': it estimates the attitude of the product/component that is potentially suitable for the reuse after the operational time.

Material Recyclability index 'M_R': is the ratio between the value of recycled material and the value of the virgin material.

Post-consumer material: material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose. This includes returns of material from the distribution chain.

Pre-consumer material: material diverted from the waste stream during a manufacturing process. Excluded is reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it.

Primary Energy Consumption (PEC): this indicator represents the cumulative consumption of primary energy for the entire process chain of the material/product.

Product: an artefact that has been created by some processes. Product here refers exclusively to goods, i.e. excluding services.

Recycled Content: Proportion, by mass, of the recycled material in a product or its parts.

Recyclability: a product or its parts are ‘recyclable’ when they can be potentially addressed to a recycling process at the EoL. Recyclability is an estimation of such potential.

Recycling: means the reprocessing in a production process of waste materials for the original purpose or for other purposes but excluding energy recovery.

Recoverability: a product or its parts are ‘recoverable’ when they can be potentially addressed to a recovery process at the EoL. Recoverability is an estimation of such potential.

Recovery: means any of the applicable operations provided in Annex II B of Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste.

Refurbishment: it is the process of restoring a product (or some of its components) to its former good condition, including also the partial replenishment with new materials.

Remanufacturing: it the industrial process whereby products are restored to useful life. During this process, the product (or some of its components) passes through a number of manufacturing steps, e.g. inspection, disassembly, cleaning, part replacement/refurbishment, reassembly and testing to ensure it meets the desired product standards.

Resource prioritisation: resources can be considered a ‘priority’ when they are ‘critical’ for relevant economic activities but face supply-risks or have other, especially environmental implications

Reusability: a product or its parts are ‘reusable’ when they can be potentially addressed to a reuse process at the EoL. Reusability is an estimation of such potential.

Reuse: means any operation by which a product or its components, having reached the end of their first use, are used for the same purpose for which they were conceived, including the continued use of a product which is returned to a collection point, distributor, recycler or manufacturer, as well as reuse of a product following refurbishment.

Substances of Very High Concern (SVHC): concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH - Regulation EC 1907/2006), it means substances that, following the precaution principle, need to be subject to careful attention and further investigated/studied

Sub-assembly: a number of components integrated into a unit forming part of a larger assembly.

Introduction

The present document is the second deliverable of the AA “Integration of resource efficiency and waste management criteria in the implementing measures under the Ecodesign Directive”[4] between DG Environment and the Commission's JRC-IES.

The project focuses on potential requirements aiming to improve resource efficiency of the products and to limit the possible environmental impacts associated with their manufacture and end-of-life. In particular four "parameters" have been analyzed in terms of methodologies for their assessment and measurement/verification procedures for the market surveillance:

- Reusability/Recyclability/Recoverability (hereinafter cited as ‘*RRR*’);
- recycled content;
- use of priority resources;
- use of hazardous substances

The relevance of the resource efficiency and waste management themes in the European policies has been underlined in Deliverable 1 on the “Review of resource efficiency and end-of-life requirements”. The review concerned the identification of ‘key issues’ about the above mentioned parameters and it involved the analysis of the current legislation, technical documentations and publications on scientific journals.

The analyzed methodologies are generally complex and mostly designed for specific purposes of the companies. However, it was observed that some ‘key issues’ that are often included/discussed in the models, such as:

- Reusability/Recyclability/recoverability as theoretical potential of products and their relationship with the effective reuse/recycle/recovery ratios;
- ‘Disassemblability’ of the product,
- Intrinsic chemical-physical properties of the materials and their change during reuse/recycle/recovery,
- Presence of contaminants,
- Previous ‘history’ of the material (including their recycled content).

Furthermore, a simple product’s scheme (generally called Bill of Materials - BOM) is often used to characterize the product’s composition and is used as basis for the further assessments and calculations.

The following chapters will describe the methodologies for the measurement and verification of the above mentioned parameters. The methods will build upon the identified key variables and a simplified scheme of BOM. Successively the methods will be illustrated with an exemplary application to a case-study.

[4] Administrative Arrangement N° 070307/2009/546207/G2.

1 Bill of Materials (BOM): basis for the calculations

1.1 Introduction

The Bill Of Material (BOM) provides a detail of the product composition. It can be also combined with additional technical details of the product. In this extended form it documents the structure and relationship between the final product, assemblies, sub-assemblies, and parts, as well as the corresponding quantities of the materials on each level.

In the scientific literature, the BOM is generally presented as a tabular structure implemented within a relational database system. This is commonly used by many companies for different tasks, including e.g. research and development, product design (especially modular design), product's testing, quality control, customer oriented production, and – as applicable – to meet legislative requirements (particularly in automotive industry and suppliers). The dimension, detail and complexity of the BOM are extremely variable, depending on the company's needs. Several software and Computer Aided Design tools have been also developed to support the drafting of the BOM.

The previous survey of the scientific literature (Deliverable 1) identified the BOM as one of main data sources for the environmental assessment of the product at the Design stage. The key role of the BOM has been underlined by several authors. For example, the MEEUP - Methodology Study Eco-design of Energy-using Products [VHK, 2005] – is based on the assessment of product's life cycle impacts from data of the BOM combined with data about the product's manufacturing, use and disposal stage. The MEEUP structured the BOM as a list of used energy and material throughout the life-cycle of the product.

Note that the present chapter was built on the basis of the outcomes of the study. The BOM is here proposed as opening Chapter because it groups basic information for the analysis. It is here firstly introduced a general structure of BOM, which represents the first common step for all the proposed methodologies. These will be discussed in the following chapters; when necessary, further details/discussions concerning the BOM have been successively added 'case by case'.

1.2 Bill of Materials and project's parameters

The present deliverable aims at defining some measurement and verification methods to assess the following parameters:

- Recyclability/Recoverability/Reusability (RRR);
- Use of recycled materials/recycled content;
- Use of priority resources;
- Use of hazardous substances.

As observed in Deliverable 1, the measurement methods have to be applicable at the product's 'Design stage'. Therefore, these methods have to be based on data available when the product has been probably not realized yet.

Generally, designers list the product's composition already at the early stage of the designing. This product's composition represents the core of the BOM and the basis for the description/analysis of the product.

The following sections illustrate the main information and the level of detail that are needed for the measurement of the previous parameters.

1.2.1 BOM and Recyclability/Reusability/Recoverability

The assessment of the product's recyclability as performed in the scientific literature [5] generally starts from a list of the product components. Successively the properties of each material are analyzed in detail in relation to its physical/chemical properties, and the availability of technologies for its recycling.

For example, the method proposed by the ISO 22628 [ISO 22628, 2002] for the measurement of the recyclability/recoverability[6] of the vehicles is based on a material breakdown of the product. This breakdown is, similar to a BOM. It includes:

- List of the materials used in the product (subdivided into metals, polymers non elastomers, elastomers, glass, fluids, organic natural materials, and other materials);
- Masses of the used materials;
- Availability of technologies for the recycling/recovery of the materials.

However, this material breakdown has some limits because it has a low level of detail and in some parts it aggregates together different materials.

Other methods for the measurement of recyclability [7] request also other additional information, depending on the deepness and complexity of the adopted parameters, including

[5] Deliverable 1, Review of resource efficiency and end-of-life requirements, Chapters 1 and 2.
[6] For a detailed description of the method, see Deliverable 1, chapter 1.1.3.
[7] Deliverable 1, chapter 2.3.

e.g. the use of connections and solders, the environmental impacts due to the manufacturing of the materials or the economic value of materials after their EoL treatments.

Furthermore, the composition of the product is not the only important information. It is also relevant how the components are connected together and where they are located in the product assembly/disassembly process. This is a key aspect, already identified in several approaches, which affects the measurement of *RRR*.

Other important additional data are:

- Concerning the recyclability: information about changes in the inherent properties of the materials due to recycling and the availability of technologies for their recycling;
- Concerning the reusability: the product modularity and the design of potentially reusable components;
- Concerning the recoverability: the energy potentially extractable by the material as e.g. by combustion (‘feedstock energy’[8]) or by other recovery treatments.

Note that the measurement of RRR requests a high level of detail: even materials that have a small mass can significantly influence the RRR of the product[9].

1.2.2 BOM and recycled content

The measurement of the recycled content of a product is mostly related to the analysis of the included materials and their manufacture. The assembly process has, instead, no influence on this parameter.

The measurement of the recycled content requires:

- the list of used materials;
- the mass of the materials
- the content of recycled waste used for the manufacturing of the materials.

The calculation of the recycled content can refer to post-consumers[10] or pre-consumer materials. This information has to be derived from suppliers’ declarations or analogous documentation (e.g. input/output flows during the manufacturing).

The recycled content of a multi-material component can be calculated as a weighed average of the recycled content of each embodied material. However, as discussed in the previous section about the RRR, it is preferable to avoid the aggregation of data concerning different materials that would cause the loss of important information.

[8] More details about the recovery of materials are presented in Deliverable 1, Chapter 2.5
[9] This topic will be successively discussed when introducing the RRR Benefits ratios (Chapter 5.6).
[10] Definitions about *Pre-consumers and Post-consumer material*: are provided in the introductory Chapter on “Definition”. For further details, see Deliverable 1 – Chapter 3.1.2.

Differently from the measurement of the *RRR*, components with small mass have not a relevant incidence on the recycled content of the product. *The BOM for the measurement of the recycled content requires*, therefore, *a lower level of detail.*

1.2.3 BOM and priority resources

"*European economies depend on natural resources, including raw materials such as minerals, biomass and biological resources; environmental media such as air, water and soil; flow resources such as wind, geothermal, tidal and solar energy; and space (land area). Whether the resources are used to make products or as sinks that absorb emissions (soil, air and water), they are crucial to the functioning of the economy and to our quality of life*"[11].

Resources can be considered a 'priority' when they are 'relevant for the economic activities, face supply-risks or have other key implication (e.g. predominantly imported critical resources, high environmental impacts during production, limited availability of the reserves[12]). Note that the assessment of priority resource requires also additional information from references and/or the scientific and technical literature.

The design of products should take care on the quantity and typology of priority resources that are used. These should be identified and listed in the BOM. Because many priority resources are contained in small traces (e.g. rare earth elements in electric and electronic components) a high detail is often necessary about the product's composition. This information can be generally collected from suppliers.

Furthermore, in order to improve the recycling/reuse of priority resources, manufacturers should design the products in order to facilitate the identification, access and disassembly of components containing priority resources.

1.2.4 BOM and hazardous substances

Concerning hazardous substances, it has been recognised that even small amounts can be harmful to humans and to the environment when released during product use or end-of-life. Consequently, a detailed analysis of a product and its component is necessary when hazardous substances are investigated (typically based on supply-chain information).

The assessment of the use of hazardous substances requests a high level of detail of the BOM. The level of detail should be defined case-by-case, depending on the investigated substance and its function in the specific product/component.

Analogously to the use of priority resources, also hazardous substances – if present - should be easy to identify and to separate in order to be addressed to specific EoL treatments.

[11] COM(2005) 670 final
[12] For further details, see Deliverable 1 – Chapter 4.

1.2.5 BOM: level of detail and supply-chain involvement

The previous paragraphs showed that different levels of detail of the BOM are needed due to the different investigated parameters. It can be summarized that (Figure 1):

- The measurement of the *RRR* needs a medium detailed BOM, focusing on the mass and typology of the individual materials and their purity, as well as their connection/assembly into the product. Specifically for reuse, additional technical information on the components and its manufacturing are required. All this information can be provided by the manufacturer or by his suppliers;
- The measurement of the Recycled content needs a less detailed BOM. However it generally involves supply-chain information about the product's components and their manufacturing;
- The assessment of the use of priority resources into products needs a detailed BOM, including also the list of small components that are generally not relevant in the assessment of the previous parameters;
- The assessment of the hazardous substances in a product necessitates of a very high detailed BOM. The needed level of detail is, however, related to the specific product and the investigated substance. Information about the content of the hazardous substances can be provided by the manufacturer or by his suppliers.

In order to simplify the compiling of the BOM, minimum thresholds of content below which a component is not relevant should/could be established, case-by-case, depending on the considered product category. This would allow focusing on more relevant components.

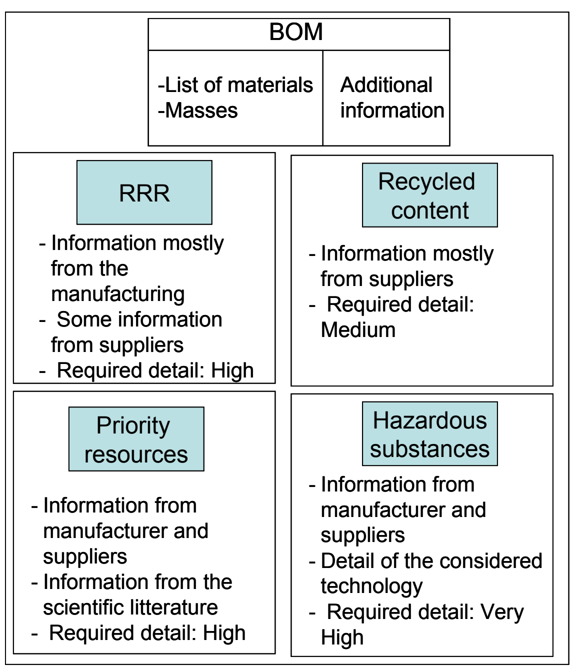

Figure 1 Level of detail required for the BOM

1.3 A proposed scheme for the BOM of a product

The present chapter proposes a scheme of BOM suitable for the scopes of the project. In view of the findings of the preceding chapter, variations can be made, depending on which parameter is analyzed. However, in view of the high possible synergies, a joint implementation in a common scheme seems beneficial.

Some elements have been identified as critical and important to be included in the BOM:

- materials typology (with a different detail level depending on the purpose of the analysis);
- employed masses;
- connections among different materials and placement of the components in the assembly/disassembly process;
- content of hazardous or other substances that negatively affect *RRR*.

It is here proposed a scheme for the BOM. The designer defines a sequence of disassembly and assigns to each assembly and sub-assemblies a univocal identification code (Figure 2). This code is based on the position of the component in the 'disassembly diagram, where an additional digit is added each time a level of this 'tree diagram' is descended.

For example the code '*2.1.2*' identifies one of the subassembly of component '*2.1'* that, in turn, is a subassembly of the element '*2*'.

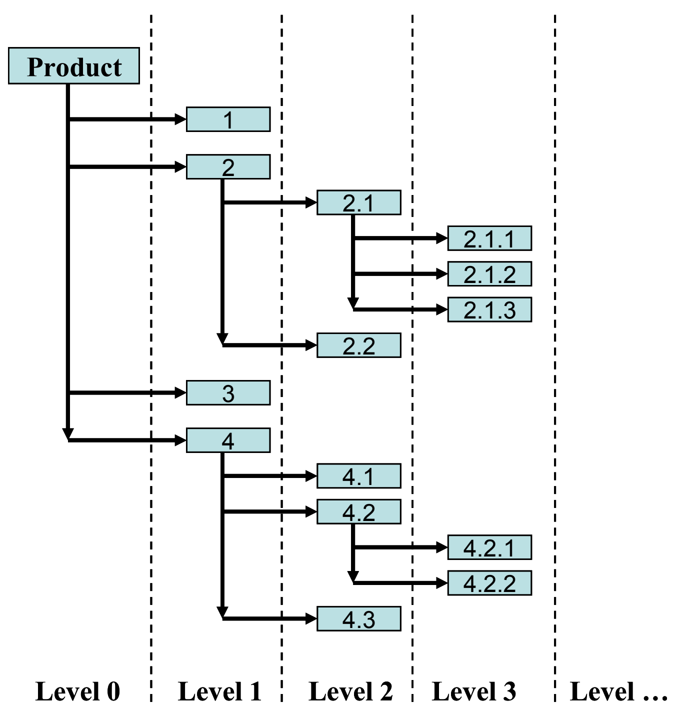

Figure 2 BOM: Representation of a product's disassembly scheme

The proposed BOM is therefore a graphical representation of the succession of the disassembly process: the product is split in his components and sub-components, similarly to the ‘reverse fishbone’ diagram[13] described in Deliverable 1.

Although quite simplified, such representation allows to sketch the structure of the product and to estimate the complexity for its disassembly.

The disassembly scheme can be generally realized on the basis of information available at the design stage. Furthermore this task requires that manufacturers would estimate how the disassembly could take place[14].

Note that “there is no universal disassembly tree for each specific product, because the actual dismantling sequence would vary with different persons or designs of disassembly streamlines. The arrangement of disassembly tree should be in line with the actual dismantling order” [Wang 2008]. It follows that designers have to represent the disassembly tree on the basis of assumed disassembly steps. Designers should choose among the different potential disassembly sequences, for example, identifying the sequence that minimize the disassembly time to a given level of targeted disassembly depth.

Assembly elements (as screws, bolds, snap-fits, adhesive, cables, solder, etc.) should be reported. It is also recommended to include in the BOM of the products the *packaging* and other *ancillary parts* (e.g. the user’s manuals) as well as consumables (e.g. toner cartridges and other parts that are foreseen to be replaced during the technical life time of the product). These, in fact, can have a relevant incidence in the overall material’s breakdown and they often have a high potential for the recycling and recovery. However, it is suggested to report these components separately because these are not part of the disassembly process of the product and, generally, they are separately disposed and treated (especially the packaging that is often directly wasted after unpacking the product).

1.3.1 Additional information for the BOM

The disassembly scheme has to be coupled with further information about each product’s component. This can be synthesized in a datasheet (Table 1) containing the following fields:

- **Component**: it describes the components that constitute the product. These are identified by:
    - The ‘*name of the component*’: this field allows to identify the component;
    - The ‘disassembly *code of the component*’: this number reflect the position in the disassembly scheme and it allows to connect the data of the table with the components of the previous diagram (Figure 2);

[13] Deliverable 1, Chapter 2.2.1.

[14] The improvement of the disassembly of the product is one of the key issues of Ecodesign of products (as underlined in Deliverable 1 – Chapter 2.2.1). It is important to address such discussion already at the early design stages of the product, when designer still have large freedom in the choice of the design parameters. In this way manufactures could also work out some solutions to improve the ‘disassemblability.

- **Component's details**: each component is then split in its constituting materials. In particular it is reported
    - the typology/name of employed materials.
    - Content's details: this entry includes additional details concerning:
        - The presence of material with an energy content potentially recoverable by incineration. In particular, the Lower Heating Value (LHW) or Higher Heating Value (HHV) should be specified (in MJ/kg);
        - The presence and mass of hazardous substance regulated by the RoHS Directive and of the Substance of Very High Concern (SVHC) Regulated by the Reach Directive[15].
        - The presence and mass of additives and coatings (as e.g. flame retardants, fillers, labels, glue, inks, paints, foams, varnishes) and/or any further impurity that could preclude or make economic not viable the reuse/recycle/recovery of the component (for further details on the potential contaminants and thresholds see Chapter 2.5.3).
    - the 'mass' detail of each component.

Table 1 BOM: example of product's datasheet

Component		**Details**		
Name	*Disassembly code*	*Materials*	*Content details*	*Mass [kg]*

Concerning the nomenclature for plastics and additives, the following standards should be followed:

- *ISO 1629 Rubbers and latices — Nomenclature* [ISO 1629, 1995].
- *ISO 11469 - Generic identification and marking of plastics products* [ISO 11469, 2000];
- *ISO 1043-1 Plastics — symbols and abbreviated terms. Part 1: Basic polymers and their special characteristics* [ISO 1043-1, 2001];

[15] On such purpose, it is interesting to cite the scheme of the 'Global Automotive Declarable Substance List (GADSL) developed by the Global Automotive Stakeholder Group (GASG) [GASG, 2001]. The GASG is a voluntary cross-industry initiative including the main automotive original equipment manufacturers, tier suppliers and material suppliers. The GASG set the Global Automotive Declarable Substance List (GADSL), a comprehensive list of materials employed in the automotive sector that are under restriction/control by some legislation, including the minimum threshold content for their accounting. However, the list is tailored for EoL legislation, and key information that affects RRR (e.g. detail on the typology of material) as well as recycled content information is missing. The GADSL has been adopted by the International Material Data System (IMDS), an Internet computer system, by which all the direct and indirect suppliers are able to insert the basic information relating to the general composition of their products in apposite spreadsheets and send them to their customers, along the entire supply chain up to the automotive firm.

- *ISO 1043-2 Plastics — symbols and abbreviated terms. Part 2: Fillers and reinforcing materials* [ISO 1043-2, 2001];
- *ISO 1043-3 Plastics — symbols and abbreviated terms. Part 3: Plasticizers* [ISO 1043-3, 1999];
- *ISO 1043-4 Plastics — symbols and abbreviated terms. Part 4: Flame retardant* [ISO 1043-4, 1999].

The 'disassembly scheme has to be coupled also with a Disassembly report that details the disassembly steps and timing.

The disassembly report represents a document that described the type of viable disassembly for each component and the disassembly timing. The report can also provide further useful information concerning: the disassembly steps, the fastening systems and possible problems that could arise during the disassembly[16].

Table 2 shows an example of the disassembly report where the following information is included:

- Disassembly steps: progressive numbering of the disassembly processes;
- Detail of the disassembly: it describe the procedure and actions needed for the disassembly;
- Disassembly code of components: coding of the disassembled components (as above introduced);
- Disassembly action: operation to remove the assembly elements, e.g. cables, screws, bolds, snap fits, solders;
- Time for disassembly: estimated/measured time necessary for the disassembly steps.

Table 2 BOM: example of datasheet for the disassembly report

Disassembly steps	Detail of the disassembly	Disassembly code of components	Disassembly action	Time for disassembly [s]
I				
II				
III				
…				

The datasheet has to be compiled only for those components that compose the most external level of each 'branch' of the 'disassembly tree'. For example, considering the product of Figure 2, the datasheet should include components: 1; 2.1.1; 2.1.; 2.1.3; 2.2; 3; 4.2.1; 4.2.2; 5.

[16] The provision of a 'disassembly report' is foreseen for the verification of some Ecolabel criteria for disassembly. For example, Deliverable 1 – Chapter 1.7.1 concerning the Ecolabel criteria for "Personal computers and portable computers", "washing machines", "refrigerators" and "vacuum cleaner".

1.3.2 Level of detail of the BOM

Although the presented BOM scheme has a general purpose and it is generally applicable to different contexts, it is necessary to define the level to which arrest the representation. A key issue is therefore the definition of the requested level of precision.

In particular, a too high level of detail of the BOM would require big efforts with, on the other side relative small advantages in terms of improving e.g. recyclability. The analysis should focus on those elements whose recycling is economically and/or environmentally attractive as to be identified in context of a related implementation of the scheme[17].

The product decomposition should stop at those components and sub-assemblies that can be considered homogeneous (concerning their physical/chemical properties) or to those components that cannot be further separated with common tools (unless processed by shredding). Certain material combinations can also be well separated by e.g. shredding without compromising recyclability, hence in such cases disassembly can stop earlier.

The requested level of detail for the report could be also indentified by thresholds. It is not necessary to further detail a component if its mass is less than a fixed percentage X%, or if the environmental benefits related to its recycling are lower than a fixed value. Such percentages and values can be defined specifically for each product category.

Concerning the detail of the data sheet, it is important that materials are well defined and as uncontaminated as practically possible. In particular, the analysis should identify and declare the presence of composite materials, tramp elements or potential contaminants that could significantly affect the recycling/recovery potential of the material.

A further level of detail could be necessary when priority resources or hazardous substances are analyzed. In this case, even small quantities of such materials could be relevant for the analysis. A common example is represented by Printed Circuit Boards which can be constituted by several precious metals, rare earth elements and hazardous compounds. In these contexts, the level of precision of the BOM has to be assessed in relation with the considered product category.

1.3.3 Compilation of the BOM

An example procedure for the compilation of the BOM is here described in order to guide a manufacturer in the collection of relevant information:

1. Determine the components, assemblies and sub-assemblies that enter in the product manufacture.

[17] Some authors [Dewhurst, 1993; Li et al., 1995] noted already early that the disassembly generally concerns the removal of the most valuable parts and it stops when the marginal return on the operation becomes uneconomical. Recycling costs determine when a disassembly process should stop. Generally, the termination of disassembly is determined on the salvage benefit, the disassembly cost, the material reprocessing cost, and the disposal cost. However, environmental benefits generally go beyond this level, while there is also an environmental optimum beyond which the additional (environmental) effort for recycling is higher than the environmental benefit. A target level is hence to be decided upon.

2. Obtain information about the material composition and mass of each component as well as its content of hazardous and other adverse materials/compounds from the suppliers (who in turn can obtain such information from their suppliers). This complete list of all the components will form the basis for the BOM.
3. Define/identify a procedure for the product's disassembly at the EoL, with a particular attention to the assembly elements. Identify assemblies that cannot be further disassembled manually and that can be potentially material-separated by shredding.
4. Measure/estimate the time for the manual disassembly of each component. The plot and report of such succession of disassembly steps and disassembly timing represents the 'disassembly scheme' of the BOM.
5. Number each component/assembly with a unique 'identifying code', considering its position in the disassembly scheme.
6. Enter the information about each component into a datasheet, with the details about the material typology, the mass and other necessary information, as specified more above.

1.3.4 Verification of the BOM

The verification of the truthfulness of the information reported in the BOM can be based on a regular (or sample-based) check by a Market Surveillance Authority.

Note that the information contained in the BOM and in the disassembly scheme refer to physical characteristics of the products that can be checked also by laboratory tests.

1.4 An illustrative example of BOM: a coffee-maker

In order to clarify the presented scheme of the BOM, a case-study application is here presented.

A hypothetical coffee-maker has been chosen and split in its components and sub-components, depicting the succession of the progressive disassembly steps (Figure 3). The related product's datasheet is shown in Table 3; Table 4 shows a detail of the disassembly process. Mass details and product's composition of the coffee-maker have been estimated.

Note that the present example is a simplified case-study that aims exclusively at illustrating the application of the methodology.

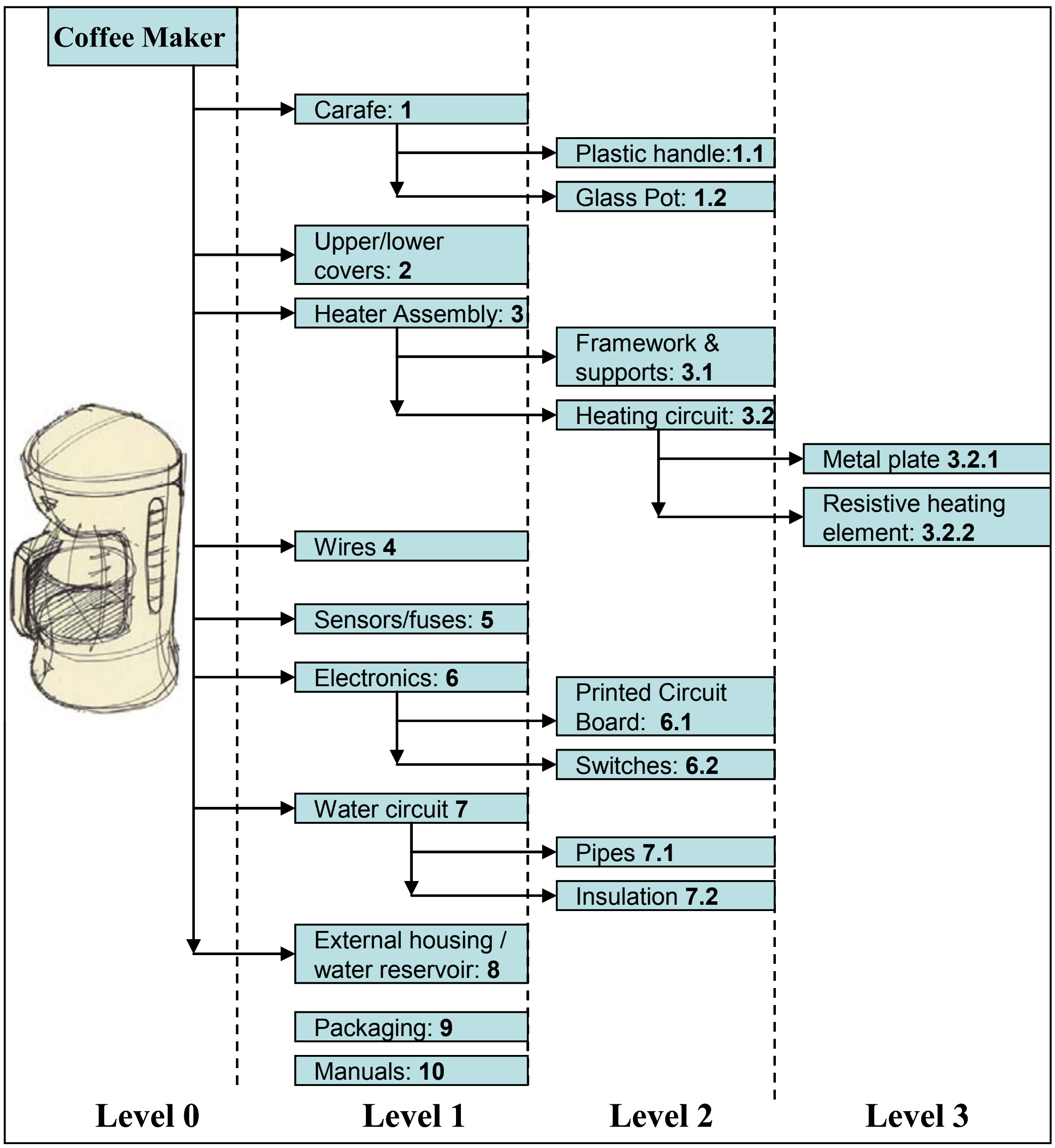

Figure 3 Example of BOM: disassembly scheme of a coffee maker

Table 3 Example of BOM: material and mass detail of a coffee-maker

Component		Details		
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*
Plastic handle	1.1	Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.05
Glass pot	1.2	Glass	Borosilicate heat resistant glass: Boron (B) content: 4%	0.5
		Steel	Screws	0.01
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A (0.05%)	0.05
Framework /supports	3.1	Steel		0.08
		Steel	Screws	0.01
Metal heating plate	3.2.1	Copper		0.1
		Steel	Screws	0.04
Resistive heating element	3.2.2	Copper		0.06
Wires	4	Copper		0.075
		Polypropylene (PP)	Combustible-LHV:46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.025
Sensors/ fuses	5	Various (metals, glass)		0.02
Printed Circuit Board	6.1	Copper		0.03
		Steel		0.02
		Aluminium		0.04
		Glass-reinforced plastic	Potential combustible but with low feedstock content	0.03
		Other		0.01
		Steel	Screws	0.01
Switches	6.2	Copper		0.01
		Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.04
Pipes	7.1	Aluminium		0.6
Insulations	7.2	Polypropylene (PP)	Combustible - LHV: 46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.05
External housing / water reservoir	8	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol-A (0.05%); Painted and labelled parts (contaminant content >1%).	0.3
Packaging	9	Low Density Polyethylene (PE-LD)	Combustible - LHV: 42 MJ/kg; Flame ret.: Red Phosphorus	0.01
		Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg	0.4
User's Manuals	10	Paper	Combustible-LHV: 18.4 MJ/kg	0.03
		Total product's mass [kg]		**2.60**

Table 4 Example of BOM: detail of the disassembly process for a coffee-maker

Disassembly steps	Detail of the disassembly	Disassembly code of components	Disassembly action	Time for disassembly [s]
I	Removal of the carafe from the coffee-maker	1	Manual removal	2
II	Manual Disassembly of the carafe: separation of the plastic handle from the glass pot	1.1 and 1.2	Unscrews	20
III	Removal of upper and lower covers	2	Remove snap fits	25
IV	Removal of the heater assembly and separation of the support from the heating circuit	3	Unscrews	35
V	Separation of the support from the heating circuit	3.1 - 3.2	Unscrews	25
VI	Separation of the heating plate and the resistive heater	3.2.1 - 3.2.2	Unscrews	40
VII	Removal of the electrical wires/cables. Cables cannot be separated manually and are addressed to shredders.	4	Hand pull	10
VIII	Removal of the sensors and fuses. Fuses cannot be further disassembled and are addressed to a shredder.	5	Hand pull	10
IX	Removal of the Printed Circuit Board. Successively the Printed Circuit Board is addressed to a shredder.	6	Unscrews	30
X	Removal of pipes	7	Hand pull	30
XI	Separation of insulation from the pipes	7.1 - 7.2	Cutting	15
XII	Removal of the Switches form the frame, and separation of the external housing anf the water reservoir. Switches are addressed to a shredder.	8 - 9	Remove snap fits	25

Note that Packaging and user manuals where accounted in the mass detail, but they are separately placed in the disassembly scheme. These additional parts can be, in fact, relevant for the overall material breakdown, but they do not need a disassembly. Furthermore, they are separately disposed.

1.5 Summary

The BOM has been identified as one of the most important data source for the measurement, at the design stage, of the product's recyclability/recoverability and the recycled content. Analogously, the BOM is important to characterize priority resources and hazardous substances contained in the product, which could be successively separated and addressed by recycling or other EoL treatments.

The compiling of the BOM is a task generally performed by the producing companies, but with very variable schemes and levels of complexity, depending on their internal needs in design context and legal obligations.

The chapter presents a simplified scheme of BOM (Chapter 1.3) where information about products components (typology and mass of the used materials) is coupled with a graphical representation of the product's disassembly scheme.

The procedure for the drafting of the BOM includes (Chapter 1.3.3):

1. Determine the components, assemblies and sub-assemblies that enter in the product manufacture.
2. Obtain information about the material composition and mass of each component as well as its content of hazardous and other adverse materials/compounds from the suppliers (who in turn can obtain such information from their suppliers). This complete list of all the components will form the basis for the BOM.
3. Define/identify a procedure for the product's disassembly at the EoL, with a particular attention to the assembly elements. Identify assemblies that cannot be further disassembled manually and that can be potentially material-separated by shredding.
4. Measure/estimate the time for the manual disassembly of each component. The plot and report of such succession of disassembly steps and disassembly timing represents the 'disassembly scheme' of the BOM.
5. Number each component/assembly with a unique 'identifying code', considering its position in the disassembly scheme.
6. Enter the information about each component into a datasheet, with the details about the material typology, the mass and other necessary information, as specified more above.

The proposed BOM scheme will be used as the starting point for the definition of the measurement and verification methods of the project's key parameters.

The level of detailed requested for the BOM is dependant on the product typology and on the purposes of the analysis (Chapter 1.3.2). It is recommended that the product decomposition should stop to those components and sub-assemblies that can be considered as homogeneous (concerning their physical/chemical properties) or to those components that cannot be further disassembled (unless specific treatments, as shredding).

The requested level of detail could be also indentified by thresholds. It is not necessary to describe further in detail a component if its mass is less than a fixed percentage, or if the salvage benefits related to its recycling are lower than a fixed value. Such percentages and values can be defined specifically for a product category.

A high level of detail is necessary when critical or hazardous substances are analyzed. In this case, even small quantities of such material could be relevant in the context of the analysis. In these contexts, the level of precision of the BOM has to be assessed case-by-case, in relation with the considered product category.

The methodology for the BOM scheme has been demonstrated upon an illustrative example of a coffee-maker.

2 A method for the measurement of ‘recyclability’, ‘reusability’ and ‘recoverability’

2.1 Introduction and overview

The purpose of this chapter is to define a general method for the measurement and verification of the three parameters: *Recyclability*, *Reusability* and *Recoverability* (*RRR*).

The Deliverable 1 has identified and analyzed some key issues concerning *RRR*. It was observed that several different approaches have been developed in the legislation, standards, guidance documents and scientific publications. Some confusion could therefore arise analyzing the different studies and discussions about the above mentioned three parameters.

The present chapter will firstly try to synthesize the main findings of the survey, providing also an integrating definition for each parameter that allows for developing an operational method. Successively the key issues already identified will be implemented in the method.

Finally the discussion will focus on the application and the verification of the proposed method.

2.2 *Recyclability*, *Reusability* and *Recoverability: general discussion and possible definitions*

2.2.1 Scope of the Chapter

The definitions already presented in Deliverable 1 about *RRR* underlined different aspects. It was observed that, especially in the scientific literature, some ‘very detailed’ definitions are provided: these definitions generally reflect the ‘core’ of a proposed measurement method. In such cases, a strict link exists among the definition and a specific unique calculation methodology, leaving out ‘de facto’ other possible approaches.

The present Chapter intends to avoid possible restrictions, and to focus on definitions about *RRR* that are suitable for different purposes and not related to a specific approach. The following sub-chapters will illustrate some key issues concerning the *RRR* definition and it will conclude in Chapter 2.2.5 with some definitions suitable for the scopes of the project.

2.2.2 Recyclability, reusability and recoverability of materials and products

A first consideration regards the need to differentiate the '*recyclability of a material*' from the '*recyclability of a product*'. Note that analogous considerations can be also formulated concerning the reusability and recoverability.

The '*recyclability of a material*' is strictly related to the inherent chemical/physical properties of the substance and the available technologies for its treatment at the End-of Life (EoL).

The '*recyclability of a product*' is, instead, a more complex matter, that considers the properties of the materials but additionally takes into consideration how the different materials and components of the product are assembled. As underlined in Deliverable 1, *the aggregation of "recyclable materials" into a product does not necessarily imply a "recyclable product*". In fact, almost all materials, if available separately, can be recycled. The problem lays in their combination in products. Hence, we underline the importance of this step.

The present document, in compliance with the project's scopes, will therefore on the '*recyclability of a product*', considering the 'recyclability of the materials' as a sub-task of the assessment.

2.2.3 Recyclability, reusability and recoverability as potentials

Almost all the discussed definitions about *RRR* focus more or less explicitly on a common point: these three parameters reflect a '*potential'* of the product. It means that they are not a 'physical' property of the product (as could be, for example, the recycled content), but they are an 'engineering' property related to the characteristics of the products and the management of its EoL.

This concept is fundamental. In fact, being *RRR* a 'potential', it is not possible to quantify them by a precise direct measurement. However, it is possible to provide a method for their reproducible and verifiable calculation from several measurable characteristics and under specific assumptions.

These assumptions are influenced by 'boundary conditions and external factors (e.g. environmental, technological, technical and economic aspects): *by changing these conditions over the time, also the estimated potentials will change*.

For example, products that are not recyclable nowadays (with currently a null 'recyclability potential') could become recyclable in the future due to the technological progress and the availability of technologies for the recycling. This would be reflected in revised legislations or other policy measures over the years.

2.2.4 Recyclability, reusability and recoverability in the waste hierarchy

The pervious survey observed that the analyzed standards and scientific studies focus mostly their attention on the measurement of the recyclability, compared to a lower interest to the recoverability of energy and the reusability of components. In particular reuse is generally discussed in relation to specific companies' case studies, without a general approach for wider product categories[18].

On the other side, the European legislation promotes the 'waste hierarchy' [EU, 2008]. It expects that designers should firstly focus on the assessment and the applicability of the partial or full reuse of the product; then, if not practicable, designers should focus on the product's recyclability. Recoverability is then the last option.

The present document intends to keep distinct the three *RRR* parameters and to generally follow the waste hierarchy. The proposed measurement method will focus firstly on the evaluation of the reusability, then on the recyclability and finally to the recoverability. This choice will affect the next steps of the research.

The current legislation often joins together the concepts of recyclability and reusability for example setting a unique requirement about reusability/recyclability or about reusability/recoverability (as in the ELV and the WEEE Directives). The proposed methodology will separately measure the reusability, then the recyclability and finally the recoverability. However, the methodology has a modular structure that allows to address the three parameters separately or to combine them.

Note that the reuse of products includes several different activities e.g. the partial or full reuse of a product, the remanufacturing and the refurbishment. Also the scopes of reuse are very different, including for example: the reuse of components for the manufacturing of high-quality[19] new products belonging to the same (or different) product category, the production of second-hand products, or the production for humanitarian purposes[20]. Each of the previous activities implies differences in the management of the reuse process. However, the scope of the present deliverable is to assess the potential for reuse at the 'design stage'. Consequently, i*t is here only considered the partial or full reuse of products by the company itself that manufactured the product*. In particular, the attention is put on the reuse options for remanufacturing[21]. Other typologies of reuse at the EoL of the products are here not considered. The modular method however, allows to be expanded to also capture such "open" reuses.

[18] The scientific survey showed that generally the studies about reusability concern the description of some specific product's components that are designed to be reused. No general methodology for the assessment of the reusability has been detected.
[19] 'High-quality' product means here a product with the same quality of a new manufactured one.
[20] For example, reuse for charity in the country or for shipping to developing countries in context of development aid.
[21] Remanufacturing includes the industrial process whereby the product (or some of its components) is restored to useful life. During this process, the product passes through a number of manufacturing steps, e.g. inspection, disassembly, cleaning, part replacement/refurbishment, reassembly and testing to ensure it meets the desired product standards.

2.2.5 Proposed definitions about reusability, recyclability and recoverability

The scope of this chapter is to provide definitions concerning *RRR* on the basis of the previous survey. These definitions will be the basis for the development of the measurement and verification methodologies.

RRR are related to the definitions of '*reuse*', '*recycle*' and '*recovery*'. On this purposes the present document refers to the definitions[22] of the Ecodesign Directive [EU, 2009].

- '*Reuse*' means any operation by which a product or its components, having reached the end of their first use, are used for the same purpose for which they were conceived, including the continued use of a product which is returned to a collection point, distributor, recycler or manufacturer, as well as reuse of a product following refurbishment;
- '*Recycling*' means the reprocessing in a production process of waste materials for the original purpose or for other purposes but excluding energy recovery;
- Recovery' means any of the applicable operations provided in Annex II B of Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste.

Definitions about *RRR* have been proposed by the Directive 2005/64/EC concerning "the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability" [EU, 2005]. However, definitions of *RRR* in the Directive 2005/64/EC are specifically addressed to vehicles and do not suffice the scope and purpose of this project.

Some general definitions are here presented. These are in-line with definitions already adopted by the European legislation, and in particular those concerning the Directive 2005/64, and the definitions about reuse/recycling/recovery in the WEEE, RoHS and Ecodesign Directives[23].

A product or its parts are 'reusable' when they can be potentially addressed to a reuse process at the EoL. ***Reusability*** *is an estimation of such potential.*

A product or its parts are 'recyclable' when they can be potentially addressed to a recycling process at the EoL. ***Recyclability*** *is an estimation of such potential.*

A product or its parts are 'recoverable' when they can be potentially addressed to a recovery process at the EoL. ***Recoverability*** *is an estimation of such potential.*

[22] For a summary of definition into legislation, standards and scientific literature, see the Deliverable 1 – Chapter 2.1.
[23] Definitions in the European Legislation were listed in Deliverable 1 – Chapter 2.1.

A particular typology of 'recovery' is the 'energy recovery', when the product is incinerated with the recovery of the energy. This parameter is interesting because it allows estimating the potential of a product to be suitable for the incineration. It is possible to define the energy recoverability as:

A product or its parts are 'energy recoverable' when they have an embodied energy content (feedstock) that ca be potentially recovered by after incineration. ***Energy Recoverability*** *is an estimation of such potential.*

Other typologies of energy recovery include, among the others, the anaerobic digestion, pyrolysis and gasification. Similarly to the definition of the 'Energy Recoverability' potential, other analogous definitions could be provided for each considered recovery alternative. As illustrative example, the following paragraphs will introduce indices related to the energy recovery by incineration. Successively, Chapter 3 will discuss the possibility to extend the indices to other energy recovery options.

Note that the above introduced definitions refer to the *RRR* as 'potentials'. As discussed in Chapter 2.2.3, these potentials are theoretical estimations of 'how much' a product (or its components) is suitable for the reuse, recycle, and recovery.

For example, if we consider the example of the coffee-machine of Chapter 1, the 'recyclability' encloses those components of the product could be recycled, considering: the structure of the product (mass and assemblies), the current level of the technologies for the recycling and the possible barriers for the recycling (disassembly efforts, contaminations among materials, degradation of the materials).

The following chapters will introduce a methodology for the measurement of the *RRR* potentials.

2.3 Key issues in reusability, recyclability, recoverability

Chapter 2.2 of the Deliverable 1 discussed some key issues concerning the *RRR* of the products. In particular three issues have been identified as crucial:

- 'product *disassemblability'*,
- *'material contamination'*,
- '*material degradation'*.

These issues have been implemented in several methods in the scientific literature, confirming therefore they key role into influencing the product's potentials to reuse, recycle and recovery[24].

The relations among these issues and *RRR* are:

- 'Product *Disassemblability'* or the 'potential to disassembly' is probably the most presented and discussed factor in the scientific survey. It deeply influences reusability, recyclability and recoverability because the efforts to disassembly the product's components represent the first, and sometimes biggest, obstacle before any further EoL treatment.
- *Material contamination* happens when incompatible materials stay combined after disassembly. Contamination is particular important for recyclability, but it is also influencing the potential for recoverability and, to a lower extent, the potential for the reusability.
- *Material degradation* is a measure of the loss of *'quality'* of the materials at the EoL. This is crucial for recyclability, concerning mainly the change of the inherent properties of materials after use and after the recycling treatments. Material degradation is also important for reuse (considering that the wear can deeply influence the reusability), while it is not relevant for the recoverability.

Note that the *RRR* are potentials assessed at the Design stage. Being not possible to foresee how and where the product will be treated at the EoL, these potential should refer to average 'EU technology mix' scenarios. This concept will be further discussed in Chapters 2.5.5 and 3.5.5, after the introduction of the methodology for the measurement of the *RRR*.

2.4 Calculation of the Reusability, Recyclability and Recoverability potentials

As discussed in Chapter 2.2.4, *RRR* are three 'potential' engineering characteristics of the products. The methodologies for their calculation are based on the following steps (Figure 4):

- Data of product's BOM (Chapter 1) are combined with assumption concerning the previously key issues (product's disassemblability, material degradation and material contamination, as described in Chapter 2.3);
- Successively the *RRR* potentials of each product's component are measured.
- Finally, the *RRR* potentials of the whole product are calculated.

The description of the methodologies in the next chapters follows a stepwise approach:

1. First (Chapter 2.4.1 and 2.4.1.1) it introduces the indices for the calculation of the product's RRR.

[24] For further details, see Deliverable 1, Chapters 2.2, 2.3 and 2.4.

2. Successively, it discusses the formulas for the calculation of sub-indices and parameters (Chapter 2.5).
3. Finally it describes the operational spreadsheets for the calculations (Chapter 2.6).

In some cases the paragraphs describe possible alternative procedures for the calculation of some parameter. It includes also alternative indices for the calculation of the overall product's *RRR*.

Note that the calculation procedure is *modular*: it means that the proposed indices are obtained as the product of different sub-indices. The modularity of the indices allows including or excluding some of the sub-indices without compromising the methodology itself. Furthermore, new sub-indices can be added in future, reflecting additional aspects that have not been investigated at this stage. Analogously, some indexes can be modified or removed on the basis of the expected targets of the decision-makers, effectiveness, and other considerations.

In particular, a further development of methodologies is proposed in Chapter 3.4, where the *RRR* indices are integrated with a methodology for the prioritisation of resources.

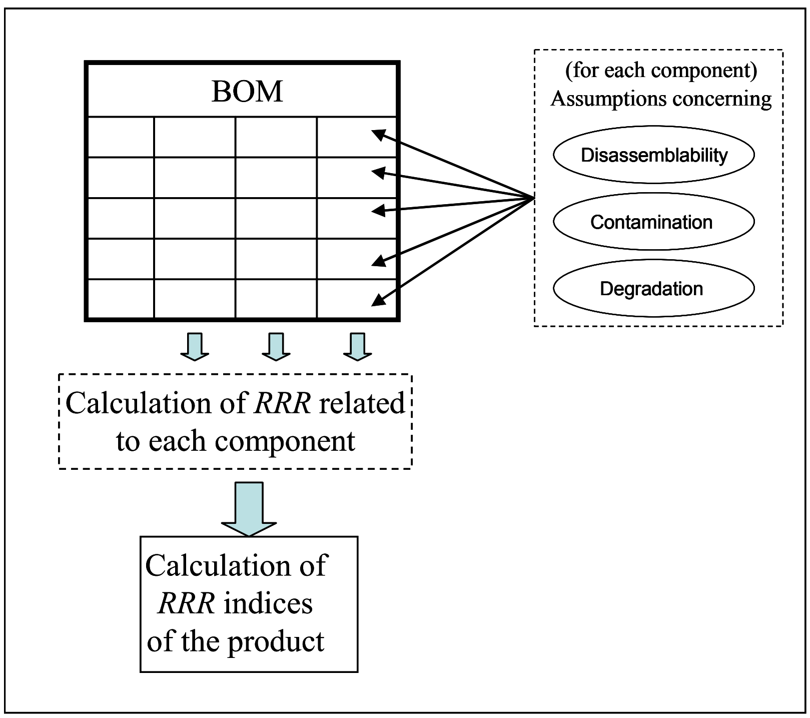

Figure 4 Methodology for the calculation of Reusability/Recyclability/Recoverability (RRR): conceptual diagram flow

2.4.1 Indices for the measurement of the RRR potentials

We define here four indices for the calculation/estimation of *RRR potentials*.

In this first phase, we define these indices as based on a 'mass ratio', similarly to other schemes already introduced (e.g. by the ISO 22628 and implemented into the European Directive 2005/64).

Successively these indices will be modified in Chapter 3.4, accordingly to the prioritisation of materials and the environmental impacts related to the reuse/recycle/recovery of the materials.

Note: In the following formulas the subscript "*i*" denotes the components of the product; the subscript "*k*" denotes the materials of the component.

'**Reusability Ratio**' (R_{Reuse}) [%]: it is the percentage (in mass) of the product that is potentially reusable. It is calculated as:

Formula 1
$$R_{\mathrm{Reuse}} = \frac{\sum_i \sum_k m_{reuse_{i,k}}}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{reuse,i\,k}$ = potentially reusable mass of the k^{th} material of the i^{th} component [kg].

'**Recyclability Ratio**' ($R_{Recycle}$) [%]: it is the percentage (in mass) of the product that is potentially recyclable. It is calculated as:

Formula 2
$$R_{\mathrm{Recycle}} = \frac{\sum_i \sum_k m_{recycle_{i,k}}}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{recycle,i,k}$ = potentially recyclable mass of the k^{th} material of the i^{th} component [kg].

The 'Energy Recoverability' potential is related to the content of materials that have an embodied energy (feedstock) that is potentially recoverable by incineration.

'**Energy Recoverability Ratio**' (***ER**_Recovery*) [%]: it is the percentage (in mass) of the product that is potentially energy recoverable by incineration. It is calculated as:

$$\textbf{\textit{Formula 3}} \qquad ER_{\text{Recovery}} = \frac{\sum_i \sum_k m_{\text{E-recovery}_{i,k}}}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{E\text{-recovery},\ i,k}$ = mass of the k^{th} material of the i^{th} component, which has an energy content potentially recoverable by incineration [kg].

2.4.1.1 An additional index concerning the Recoverability

The recovery of materials, as defined by the Annex II B of Directive 2006/12/EC, includes both the recycling treatments and the energy recovery. Therefore it is possible to introduce a new index, called 'Recoverability Ratio' ($R_{Recovery}$), that includes the components that are potentially recyclable ($m_{recycle,i,k}$ as previously defined in formula 2) and, also, those components that have an energy content potentially recoverable by incineration ($m_{E\text{-recovery},\ i,k}$ as previously defined in formula 3). The 'Recoverability Ratio' can be defined as:

'**Recoverability Ratio**' (***R**_Recovery*) [%]: it is the percentage (in mass) of the product that is potentially recoverable. It is calculated as:

$$\textbf{\textit{Formula 4}} \qquad R_{\text{Recovery}} = \frac{\sum_i \sum_k (m_{recycle_{i,k}} + m_{E-recovery_{i,k}})}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{recycle,i,k}$ = mass of the k^{th} material of the i^{th} component potentially recyclable [kg];
- $m_{E\text{-recovery},\ i,k}$ = mass of the k^{th} material of the i^{th} component that has an energy content potentially recoverable by incineration [kg].

As sub-definition it can be assumed that:

$$\textbf{\textit{Formula 5}} \qquad m_{\text{recovery}_{i,k}} = (m_{recycle_{i,k}} + m_{E-recovery_{i,k}})$$

- $m_{recovery,\ i,k}$ = mass of the k^{th} material of the i^{th} component that can be recovered.

<u>**Note**</u>: IF: $(m_{recycle\,i,k} + m_{recovery\,i,k}) > m_{i,k} \Rightarrow$ THEN: $(m_{recycle\,i,k} + m_{recovery\,i,k}) = m_{i,k}$;

ELSE: $m_{\text{recovery}_{i,k}} = (m_{recycle_{i,k}} + m_{E-recovery_{i,k}})$

It is important to note that some materials are potentially both recyclable and energetically recoverable (as for example, paper, cardboard or some plastics). A material can therefore contribute to both the recycling (the '$m_{recycle}$' of the previous formula 4) and to the energy recovery ('$m_{E\text{-}recovery}$'). However it is assumed that each material cannot contribute for more than 100% of its mass. It is therefore important to avoid potential double counting of the materials in formula 4.

The following sections will illustrate the procedure to calculate the values of the terms '$m_{recycle}$' and '$m_{E\text{-}recovery}$' concerning each k[th] material of the i[th] component having a mass $m_{i,k}$. successively the term '$m_{recovery,\ i,k}$' is calculated (in accordance to formula 5). The analyst has finally to check that the value of '$m_{recovery,\ i,k}$' would be minor or, at maximum, equal to the mass $m_{i,k}$ of the considered material.

If the calculated value would result higher than the mass $m_{i,k}$ then the analyst has to set it to $m_{i,k}$ (see the note in the previous box for formulas 4 and 5). This condition represents a 'physical constraint' of the mathematical methodology.

2.4.2 Verification of RRR indices

The verification of the *RRR* indices is based on self-declarations of the manufacturer supported by technical documentation available before the product is put into the market and provided on request.

Declarations could be verified e.g. by a Market Surveillance Authority (MSA) that can check the truthfulness of provided information (e.g. BOM, the 'disassembly scheme' and the additional information about the product's disassembly) and successively would follow the calculation done by the manufacturer by apposite 'calculation data sheet'

Further details about the verification of the calculation of each parameter will be provided in the next paragraphs, after the introduction of the calculation procedures and the description of the indices and sub-indices.

2.5 Calculation of the RRR potentials

2.5.1 Calculation of 'm_{Reuse}', '$m_{Recycle}$' and '$m_{E\text{-}Recovery}$' masses

The previously introduced indices (Chapter 2.4.1) are based on the calculation of the fraction in mass of potentially reusable ($m_{reuse,i,k}$), recyclable ($m_{recycle,i,k}$), recoverable ($m_{recovery,i,k}$) and energy recoverable ($m_{E\text{-}recovery,i,k}$) components. Each fraction can be calculated as:

$$m_{reuse_{i,k}} = m_{i,k} \cdot D_{i,k} \cdot M_{D_{i,k}} \quad \textbf{Formula 6}$$

- $m_{reuse,i,k}$ = potential reusable mass of the k^th material of the i^th component [kg]
- $m_{i,k}$ = mass of the k^th material of the i^th component, which is suitable for reuse [kg]
- $D_{i,k}$ = disassembly index of the k^th material of the i^th component [%]
- $M_{D,i,k}$ = material degradation index for reusability of the k^th material of the i^th component [%]

$$m_{recycle_{i,k}} = m_{k,i} \cdot D_{i,k} \cdot C_{1_{i,k}} \cdot M_{R_{i,k}} \quad \textbf{Formula 7}$$

- $m_{recycle,i,k}$ = potential recyclable mass of the k^th material of the i^th component [kg]
- $m_{i,k}$ = mass of the k^th material of the i^th component, which is suitable for recycling [kg]
- $D_{i,k}$ = disassembly index of the k^th material of the i^th component [%]
- $C_{1,i,k}$ = contamination index for recyclability of the k^th material of the i^th component [%]
- $M_{R,i,k}$ = material degradation index for recyclability of the k^th material of the i^th component [%]

$$m_{E-recovery_{i,k}} = m_{i,k} \cdot D_{i,k} \cdot C_{2_{i,k}} \quad \textbf{Formula 8}$$

- $m_{E\text{-}recovery,i,k}$ = potential energetically recoverable mass of the k^th material of the i^th component [kg]
- $m_{i,k}$ = mass of the k^th material of the i^th component, which has an energy content suitable for recovery [kg]
- $D_{i,k}$ = disassembly index of the k^th material of the i^th component [%]
- $C_{2,i,k}$ = contamination index for energy recoverability of the k^th material of the i^th component [%]

The following paragraphs introduce the formulas for the calculation of the disassembly index, the contamination index and the degradation index.

2.5.2 An index 'D' for the 'disassemblability'

Considering that products are generally a complex and multi-material aggregates, it is necessary to access and to separate those parts and components that are suitable for reuse/recycle/recovery.

The 'Disassembly index' "**D**" *estimates, in percentage [%,], the aptitude of the product's components to be separated and addressed to further EoL treatments*. As from the survey of Deliverable 1, disassembly can occur:

- Manually: technicians are engaged to disassembly and unfasten each component, by using common tools[25]. It allows a good status of the disassembled parts, which are often also still suitable for reuse. On the other side, manual disassembly typically implies higher costs;
- Mechanical: the products are inserted into machines (e.g. shredders) that typically chop the product into small parts. Metals (ferrous and non-ferrous) are then partially recovered, for example by sorting them into special variable electro-magnetic fields. Some plastics can be also separated (for example, by means of density separators). Compared to the manual disassembly, the mechanical shredding grants lower separation percentages and lower quality of the materials (due to high level of contamination); reuse is typically excluded. Furthermore, the shredding is characterized by high percentage of 'residues', highly contaminated that can be partially recoverable (after a thermal treatment, under some restrictions[26]) or disposed into landfills,;
- Mixed disassembly: this is the most common disassembly option, regarding a first manual disassembly of the biggest and most valuable parts (e.g. metals, precious components, homogeneous plastic components, reusable components) or high polluting parts (e.g. fluids, components contaminated by hazardous substances), and successively a mechanical shredding of the remaining parts. This solution tries to optimize the disassembly, benefiting of the advantages of both the previous systems.

'Disassemblability' affects in a different way the *RRR*. In particular, the reuse of a product (or its components) requires a careful disassembly, in order to preserve the product/component from possible damages. Disassembly for recycling can be destructive, but it aims to separate different materials avoiding contamination. Finally, disassembly for energy recovery can be destructive and can also tolerate some contaminants within certain limits.

Therefore the value of the Disassembly index "**D**" can be different when related to the reuse, the recycling or the recovery.

2.5.2.1 Disassembly index for Reuse

As described in Chapter 2.2.3, 'reusability' implies a potential for reuse estimated by designers/manufacturers at the design stage. The reusability involves therefore those products/components that have been specifically designed to be partially or fully reinserted after minor treatments.

When a designer/manufacturer claims the reusability of the product/component he also has to prove that the product/components can be properly disassembled.

[25] It is assumed that the manual disassembly is done by an 'average' technician (meaning a technician without any specific training/information on the product to disassembly) with 'common' tools (e.g. tools normally adopted by repairers as screw drivers, hammers, wrenches, bolt fastener, etc.).

[26] In the scientific literature, some alternative uses of the shredding residue have been identified (including incineration, hydrolysis to light fuel oils, or combustible for cement plants) [Boughton and Horvath, 2006]. These alternatives, however, are often experimental and characterized by several technological difficulties, high costs and environmental impacts. Landfill of the shredded residue is still the most common option worldwide.

For reusable products/components, *the disassembly index "**D**" is assumed 100%.*

2.5.2.1.1 Verification of the disassembly index for Reuse

The 'disassemblability' is calculated by the manufacturer as an intermediate step for the calculation of the RRR indices. The verification of the 'disassemblability' is therefore part of the verification process of the RRR indices, based on self-declaration of the manufacturers supported by technical documentation.

For example, the documentation to be provided concerning the 'disassemblability' claims for reuse can include:

- The declaration that the product/component was specifically designed for reuse.
- The description about how the product/component can be disassembled without compromising its functionalities;
- The description of the processes and check that the products/components has to undergo before the reuse;
- The description of the manufacturing process where the reusable product/component will be inserted;
- The description of the procedures and actions that the company has activated for the take-back of the reusable product/component.

2.5.2.2 Disassembly index for Recycling/Recovery

The disassembly index "**D**" for Recycle/Recovery is estimated on the basis of the BOM and the related disassembly scheme.

First we propose a 'simplified' approach based only on the disassembly scheme and the 'time for disassembly'.

Successively, we introduce some alternative procedures that involve also the parameters mass or the economic value of the components. It is, in fact, supposed that components with higher mass or higher value (after the recycling) are more probably diverted from the other components, even engaging higher efforts for the disassembly.

2.5.2.2.1 Simplified procedures for the Disassembly index for Recycling and Recovery

In the simplified approach, the designer analyzes the product, the disassembly process, the typologies of disassembly (manual, mechanical or mixed) that applies for each component and the needed disassembly timing. These data can be derived from the BOM scheme of Chapter 1.

Figure 5 shows an example of disassembly scheme. The figure reports the product's components, the steps necessary to disassembly the product, the disassembly codes for the components, the typology of disassembly (manual and mechanical), and the time necessary for the manual disassembly.

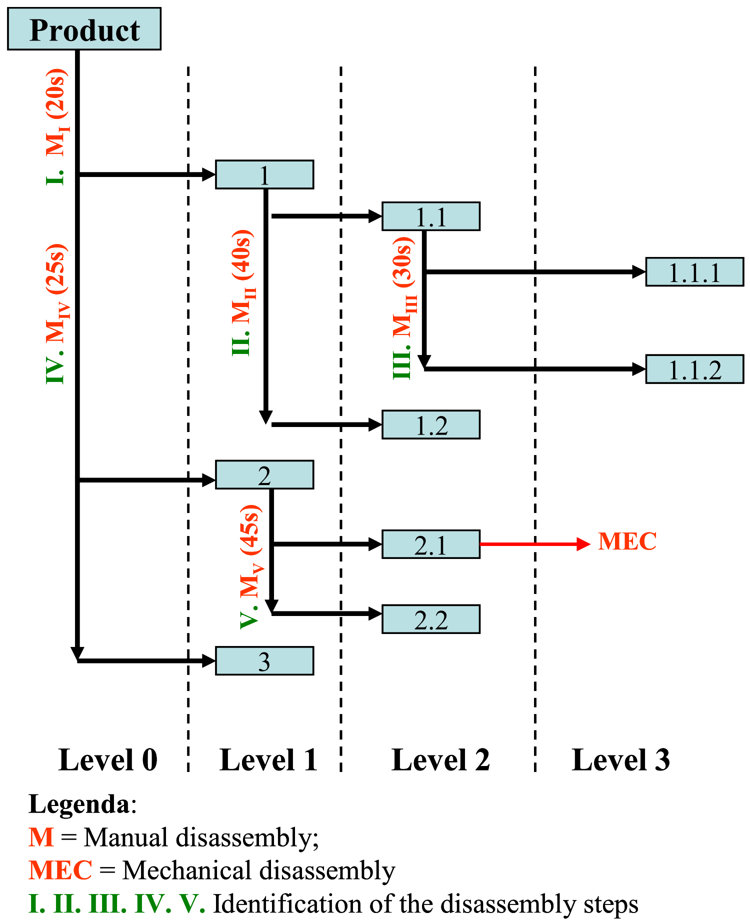

Figure 5 **Example of the disassembly scheme with the detail of the disassembly process and timing**

To estimate the Disassembly index in the simplified procedure it is necessary to define two parameters for each component:

- The number ‘*n*’ of steps that are necessary to separate the considered component;
- The overall time ‘*t*’ that is necessary to separate the considered component.

Both those parameters can be extracted from the BOM scheme.

Let us consider, for example, the component 1.2 of Figure 5. To disassembly the component 1.2 it is necessary first to separate the component 1 (disassembly step I; manual disassembly timing “M_I” = 20 seconds); successively the component 1.2 is separated from the component 1.1 (M_{II} = 40s). It results that:

- Number of necessary steps: n = 2 (steps I and step II);
- Time ‘t’ for manual disassembly: t = 60 s ($M_I + M_{II}$).

Let us consider the disassembly of component 2.1. It is necessary first to separate the component 1 (M_I = 20s); then the component 2 it is separated (M_{IV} = 20s); finally the component 2.1 is separated from the component 2.2 (M_V = 45s). Component 2.1 cannot be further disassembled manually but can be should be addressed to shredding. It results that:

- Number of necessary steps: n = 3 (steps I, step IV and step V);
- Time 't' for manual disassembly: t = 90 s ($M_I + M_{IV} + M_V$).

The two parameters, 't' and 'n'[27], can be successively used to estimate the disassembly index, as follows:

- if only manual disassembly occurs, the 'D_{Manual}' index is estimated from Table 5;
- if only mechanical disassembly is feasible, the '$D_{Mechanical}$' index is estimated as in Table 6[28];
- if a component can be mechanically disassembled after some manual disassembly steps, the 'D' index is calculated as follows:

$$\textbf{\textit{Formula 9}} \quad D_{mixed} = D_{Manual} \cdot D_{Mechanical}$$

Where:

- D_{mixed} = disassembly index for a mixed manual/mechanical disassembly;
- D_{Manual} = disassembly index for the component considering the manual disassembly of the component before the mechanical shredding (from Table 5);
- $D_{Mechanical}$ = disassembly index for mechanical shredding (from Table 6).

[27] The parameter 'n' has been here considered because it is assumed that the more are the necessary steps for the disassembly, the more potential difficult is the disassembly.

[28] Values in Table 4 are based on average estimation provided in the scientific literature. Anyway this percentage is deeply influenced by the employed technology and on the composition of the products inserted into shredder. Concerning plastics, some post-shredder treatments allow separating some plastics; however their 'quality' is generally poor, with lot of contaminants that actually make the recycling problematic. It was here assumed that plastics from shredders are not suitable for recycling (D=0%) and these can be only partially separated for energy recovery (D=50%). For further details see *Deliverable 1 – Chapter 2.3.3 and Chapter 2.4.*

Table 5 Example of table for the calculation of the disassembly index 'D_{Manual}' for manual disassembly[29]

Number 'n' of steps for the manual disassembly	Manual disassembly: D_{manual} [%]				
	Time 't' for disassembly				
	$t \leq 60$ s	$60\text{ s} < t \leq 120$ s	$120\text{ s} < t \leq 240$ s	$240\text{ s} < t \leq 360$ s	$t > 360$ s
n = 1	100%	90%	80%	70%	60%
n = 2	98%	88%	78%	68%	58%
n = 3	96%	86%	76%	66%	56%
n = 4	94%	84%	74%	64%	54%
n = 5	92%	82%	72%	62%	52%
n = 6	90%	80%	70%	60%	50%
n = 7	88%	78%	68%	58%	48%
n = 8	86%	76%	66%	56%	46%
n = 9	84%	74%	64%	54%	44%
n = 10	82%	72%	62%	52%	42%
…	…	…	…	…	…

Table 6 Example of table for the calculation of the disassembly index '$D_{Mechanical}$' for mechanical shredding[30]

Material	$D_{mechanical}$ [%]
Iron	95%
Precious metals (platinum group, gold, silver)	95%
Aluminium	90%
Copper	85%
Other metals	80%
Plastics (*)	50%
Other materials	0%

(*) values refer to disassembly for the energy recovery. For reuse/recycle D = 0%

For example, let us consider the previous component 1.2 of Figure 5. It can be disassembled manually and it does not need further mechanical disassembly. Therefore, from Table 5 it results that the disassembly index of component 1.2 is:

$$\textbf{\textit{Formula 10}} \quad D_{manual\,(1.2)} = 98\% \qquad (t = 60;\, n = 2)$$

Concerning a mixed manual/mechanical disassembly, let consider the previous component 2.1 of Figure 5. It is supposed that component is manually disassembled until level 2 and then it addressed to shredder (to separate steel and copper). The disassembly index is:

[29] The values of the table are only illustrative of the proposed methodology.
[30] The table is only illustrative of the proposed methodology. The reported values are not representative of the effective disassembly process.

$$D_{mixed(2.1)} = D_{manual(2.1)} \cdot D_{mechanical} \quad \textbf{\textit{Formula 11}}$$

- $D_{manual,\,2.1}$ = Manual disassembly index of component 2.1 = 86 % (n = 3 ; t = 90s ; Table 5);
- $D_{mechanical,\,Copper}$ = 85% (copper ; Table 6);
- $D_{mechanical,\,Steel}$ = 95% (steel ; Table 6).

It results that:

- Concerning the copper: $D_{mixed(2,1)} = 86\% \cdot 85\% = 73.1\%$
- Concerning the steel: $D_{mixed\ (2,1)} = 86\% \cdot 90\% = 77.4\%$.

The above mentioned procedure to calculate the ‘D’ index is synthesized in Figure 6.

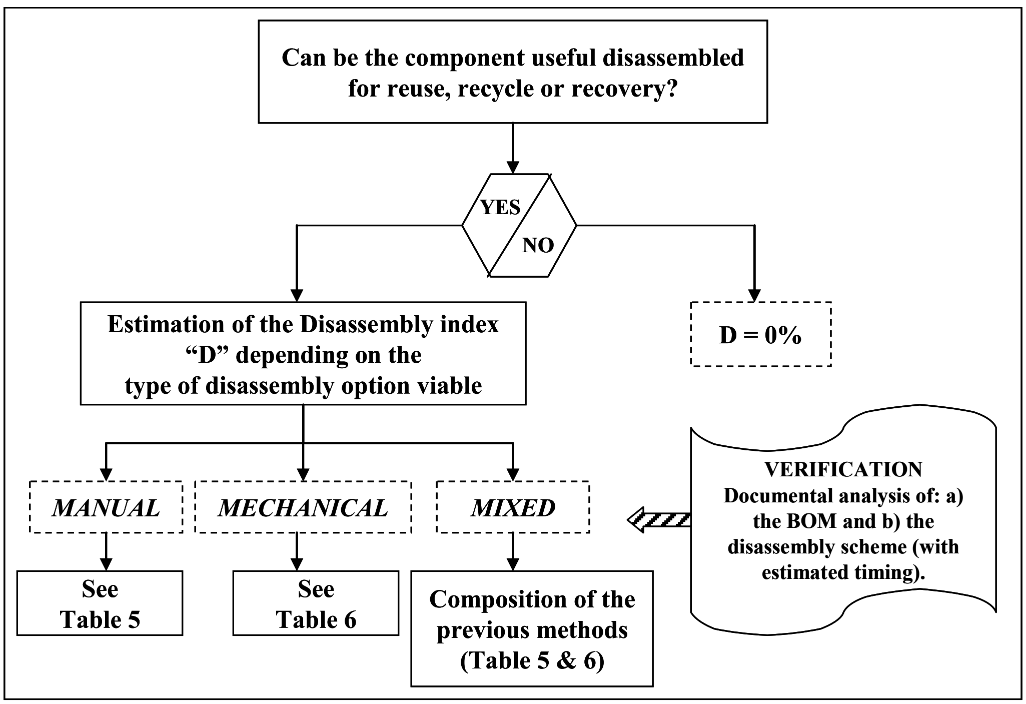

Figure 6 Procedure for the calculation of the Disassembly index “D”

2.5.2.2.2 Alternative procedures for the Disassembly index for Recycling and Recovery

Alternative procedures for the calculation of the ‘D’ index during the manual disassembly are here discussed. The mechanical and mixed disassemblies will be estimated as in the previous procedure (Figure 6).

Firstly, the component's mass 'm' is introduced into the estimation. In particular, it is assumed that: the higher is the mass of the component, the higher is the 'probability' that such component will be disassembled.

The calculation of the D_{manual} index uses Table 7. Note that this table is only illustrative of the methodology. Specific tables should be compiled with the support/suggestions of manufacturers and 'disassemblers', in order to identify the suitable 'mass' and 'time' ranges. Different disassembly tables could be also set for different product categories.

Table 7 Example of table for the calculation of the index 'D' for manual disassembly (alternative procedure) [31]

Mass of the component: 'm'	**Manual disassembly: D'_{manual} [%]** Time 't' for disassembly				
	t ≤ 60 s	60 s < t ≤ 120 s	120 s < t ≤ 240 s	240 s < t ≤ 360 s	t > 360 s
m ≥ 5 kg	100%	90%	80%	70%	60%
3 ≤ m < 5 kg	95%	85%	75%	65%	55%
1 kg ≤ m < 3 kg	90%	80%	70%	60%	50%
0.5 kg ≤ m < 1 kg	85%	75%	65%	55%	45%
0.1 kg ≤ m < 0.5 kg	80%	70%	60%	50%	40%
m < 0.1 kg	75%	65%	55%	45%	35%

A further variation of such methodology includes the value '*V*' of the components. This is strictly related to the mass, being '*V*' the product of the mass and the specific value '*v*' of the component.

Note that the specific value '*v*' changes when the component is addressed to 'Reuse', 'Recycle' or 'Energy Recovery' (if applicable).

Furthermore, the specific value 'v' is affected by price variations/fluctuations and several uncertainties. For example, it is difficult to estimate, at the design stage, the economic value that a components will have at the EoL. This is due to the uncertainties related to the length of the operating time, the user's behaviours and the location of the product. Price fluctuation can be considered a limit of the procedure. For such reason, this procedure is here introduced as a possible alternative.

The disassembly index could be calculated as in Table 8. The table has been calculated supposing a cost of manual disassembly of 0.3 € per minute.

The table estimated that disassembly occurs (D= 100%) when the cost for the manual disassembly is lower than the value of the component.

It could also be assumed that the mechanical or mixed disassembly takes place if the combined costs (manual plus mechanical) for the disassembly are lower than the estimated value of the component.

[31] The table is only illustrative of the proposed methodology. The reported values are not representative of the effective disassembly process.

Table 8 Example of table for the calculation of the index 'D' for manual disassembly (alternative procedure) [32]

Value of the component: V	Manual disassembly: D'_{manual} [%]					
	Time 't' for disassembly					
	t ≤ 60 s	60 s < t ≤ 120 s	120 s < t ≤ 180 s	180 s < t ≤ 240 s	180 s < t ≤ 240 s	240 s < t ≤ 360 s
V ≤ 0.3 €	100%	0%	0%	0%	0%	0%
0.3 € > V ≥ 0.6 €	100%	100%	0%	0%	0%	0%
0.6 € > V ≥ 0.9 €	100%	100%	100%	0%	0%	0%
0.9 € > V ≥ 1.2 €	100%	100%	100%	100%	0%	0%
1.2 € > V ≥ 1.5 €	100%	100%	100%	100%	100%	0%
1.5 € > V ≥ 1.8 €	100%	100%	100%	100%	100%	100%

2.5.2.3 Verification procedure for the 'disassemblability'

The 'disassemblability' is calculated by the manufacturer as an intermediate step for the calculation of the RRR indices. The verification of the 'disassemblability' is therefore part of the verification process of the RRR indices, based on self-declaration of the manufacturers supported by technical documentation.

For example, the documentation to be provided concerning the 'disassemblability' claims for reuse can include:

- The BOM with the detail of the disassembly scheme and the material breakdown as described in Chapter 1;
- A disassembly report (see Chapter 1.3.1 for details).

Concerning the verification of the 'disassemblability' based on the alternative procedures of Chapter 2.5.2.2.2, the manufacturer should provide additional information about the economic values of the components for their recycling, reuse, or recovery.

[32] The table is only illustrative of the proposed methodology. The reported values are not representative of the effective disassembly process.

2.5.3 An index for the materials' contamination

Even if one or more materials are potentially reusable, recyclable or recoverable, their combination might be not.

Some plastics, for example, cannot be recycled if contaminated by other materials. As observed by some authors, "*in some cases, one percent in weight of contamination is enough to ruin a batch of high grade plastics for recycling*".

The presence of contaminants, such as tramp metals or hazardous substances, can preclude or make economically not viable the recycling of metals.

Even recoverability is influenced for example by contamination of hazardous substances (such as heavy metals). Some substances/compounds can also interfere with the incineration process causing the production of hazardous pollutants (as PVC or other chlorinated compounds) and/or requiring additional efforts for the gas cleaning and ash management. On such purpose, some researchers also raised doubts about the use of the shredding residual for the energy recovery[33].

Contamination can also interfere with reusability. In fact, contaminants (due, for example, to a wrong disassembly) could make the component not suitable for the reuse. The design of potential reusable components should identify and avoid possible sources of contaminants during the product's lifecycle.

Possible actions to avoid contamination and support the *RRR* are:

- To avoid incompatible materials in the components received at the final levels of disassembly (e.g. Tables 9 and 10 present some examples of incompatibilities for the recycling among plastics and metals, respectively);
- To identify and reduce surface covers (like paints, varnishes) and bonding agents (glues and adhesives) because of their potential to contaminate materials to be recycled;
- To mark materials, especially plastics, above a minimum mass[34]. Several standards have been also introduced to regulate nomenclature and labelling of plastics, rubbers and polymers (see Chapter 1.3 for details);
- To avoid moulded-in or glued-on metal, unless metal inserts can be easily removed;
- To avoid the use of acoustical foam, coatings and labels that could reduce the recyclability of the product;
- To investigate and discuss with designer the selection of adhesives and their effect on component recyclability;
- To reduce, when possible, the number of different materials.

[33] Concerning this topic, see Deliverable 1 – Chapter 2.3.4.
[34] For example some standards suggest marking plastic components bigger than *100 g* as the [IEE, 2009].

Table 9 Example of compatibility for recycling among thermoplastics [ECMA-341, 2008]

Mixture component \ Excess component	ABS	ASA	PA	PBT	PBT+PC	PC	PC+ ABS	PC+ PBT	PE	PET	PMMA	POM	PP	PPE	PPE+PS	PS	PVC	SAN	TPU
ABS	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	+
ASA	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	+
PA	@	@	+	@	@	■	■	■	@	@	@	@	@	■	@	@	■	@	+
PBT	+	+	@	+	+	+	+	+	@	@	@	@	@	@	@	@	■	+	@
PBT+ PC	+	+	@	+	+	+	+	+	@	@	@	■	@	@	@	@	■	+	+
PC	+	+	■	+	+	+	+	+	@	+	+	■	@	@	@	@	■	+	@
PC+ ABS	+	+	@	+	+	+	+	+	@	+	+	@	@	@	@	@	■	+	+
PC+ PBT	+	+	■	+	+	+	+	+	@	+	+	@	@	@	@	@	■	+	+
PE	■	■	@	■	■	@	■	■	+	■	■	■	+	■	@	■	@	■	@
PET	+	+	@	+	+	+	+	+	@	+	@	@	@	@	@	@	@	@	@
PMMA	+	+	@	■	■	+	+	+	@	@	+	@	@	@	@	@	@	@	@
POM	@	@	@	@	@	■	■	■	@	@	■	+	@	@	@	@	@	@	@
PP	■	■	@	■	■	■	■	■	@	■	■	■	+	■	@	■	@	■	@
PPE	@	@	@	@	@	@	@	@	@	@	@	@	@	+	+	+	■	@	@
PPE+ PS	@	@	+	@	@	@	@	@	@	@	@	@	@	+	+	+	■	@	@
PS	@	@	@	@	@	@	@	@	@	@	@	@	@	@	+	+	@	@	@
PVC	+	+	■	■	■	■	■	■	@	■	+	+	@	■	@	@	+	+	+
SAN	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	@
TPU	+	+	+	■	+	+	+	+	@	+	+	+	@	@	@	@	+	+	+

+ Good compatibility over a wide range of mixtures

@ Limited compatibility for small excess component amounts

■ Incompatible

Legend of the acronyms: ABS (Acrylonitrile-butadiene-styrene); ASA (Acrylonitrile-styrene-acrylate); PA Polyamide; PBT (Polybutyleneterephthalate); PC Polycarbonate; PE Polyethylene; PET (Polyethyleneterephthalate); PMMA (Polymethylmethacrylate); POM (Poly oxymethylene); PP Polypropylene; PPE (Polyphenyleneether); PS Polystyrene; PVC (Polyvinylchloride); SAN Styrene-acrylonitrile; TPU Thermoplastic polyurethane.

Table 10 Examples of incompatibility for recycling among metals [Brezet and van Hemel, 1997]

Metals (processed by smelters)	Penalty elements (seriously decrease the value of the recyclable fraction)	Knock-out elements (decrease value of the recyclability to zero)
Copper(Cu)	As, Sb, Ni, Bi, Al	Hg, Be, polychlorobenzene
Aluminium (Al)	Si	Cu, Fe, polymers
Iron (Fe)	Sn, Zn	Cu

An example of incompatibility among non-metallic materials is represented by the addition of boron oxides into glasses. Borosilicate glasses have an improved resistance to thermal shocking, and for this reason they employed into several sectors (e.g. electronic equipment, vacuum-tubes, medical tools, kitchen tools, etc.). On the other side, borosilicate glasses cannot be recycled because they do not fully melt in the furnaces and can compromise the mechanical properties of the recycled glass.

Note that the incompatibilities in Table 9 and 10 are related to the technologies for the recycling. Some incompatibilities could be overtaken by the technological progress; on the other hand new incompatibilities could arise because of new materials or additives introduced in the market. Therefore, it is necessary to periodically check and revise these lists in order to compile a comprehensive database. Incompatibilities in Table 9 and 10 should be considered as only illustrative for the purposes of the proposed methodology.

The materials' Contamination index "***C***" *estimates how much the presence of contaminants into the materials could potentially interfere with the product's reuse, recycle or recovery.* For the calculation of the *RRR* indices, it is also important to introduce the complementary index of *Absence of contamination* ***C'*** [%] defined as:

Formula 12 $C' = 1 - C$

The "*C*" index related to a component has the structure of a percentage 'depreciation factor' [%]. The more a contaminant is not compatible with reuse, recycle or recovery of a material, the bigger should be the "***C***" index.

In order to estimate the contamination index, manufacturers and designers have to check if contaminations occur and, successively, how deeply they can affect the reuse, recycle or recovery of the product/component.

The contaminants affect in different way the potential reuse, recycle or recover of the product. For example, the presence of contamination by mercury can affect the recyclability and recoverability of a component, but not the reusability (where a component is fully reused without further treatments); the presence of labels or inks can instead sensibly affect the recyclability, partially the reusability, but not the recoverability.

Different percentages of the 'Contamination index C' are then defined: 'C_1' concerning recycle and 'C_2' concerning reuse. Contamination affecting reusability can generally occur due to an incorrect use or disassembly of the product; these elements take part in the calculation of material degradation after the use (as explained in Chapter 2.5.4.1) and therefore they are not considered here.

The procedure for the calculation of the 'C' index is (Figure 7):

- To identify if contaminations among components occur or not. Estimations should be based on the know-how of manufacturers and designers. Table 9 and Table 10 can represent a tool for the preliminary check[35].
- To assess (by means of Table 11 and 12, and on the basis of the named know-how) how deeply contaminations can affect the recycle or recovery of the components.

[35] Additional and more updated tables concerning material incompatibilities could be defined with the support of stakeholders, mainly manufacturers, designers and recyclers. Table here presented have to be intended only illustrative of the proposed methodology.

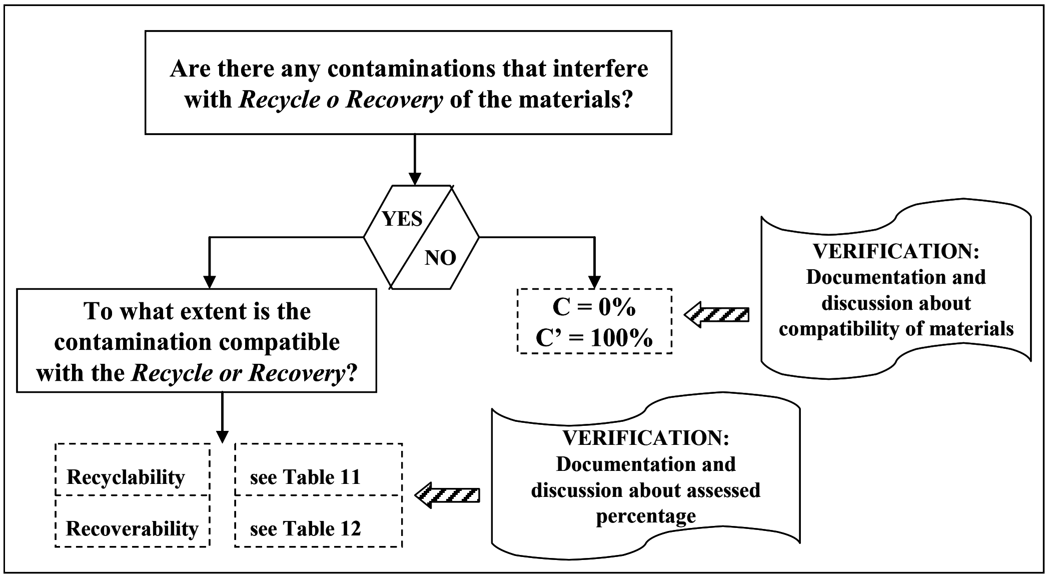

Figure 7 Procedure for the assessment of the materials' Contamination indices C and C'

Table 11 Example of table for the calculation of the 'Contamination index' for recyclability[36]

To what extent the contamination affect the *Recyclability* of the materials?			
	C_1	C_1'	Note
High	100%	0%	- Contamination regards hazardous substances regulated by the RoHS Directive and substances classified as 'Substance of Very High Concern (SVHC)' by the REACH Directive (contaminant content higher than 0.1% of the component mass). - Contamination regards incompatible plastics as in Table 9 (assuming a manual disassembly and contaminant content higher than 1% of the component mass). - Contamination regards knock-out elements as in Table 10 (assuming a manual disassembly and contaminant content higher than 1% of the component mass).
Medium	50%	50%	- Contamination regards plastic with limited compatibility as in Table 9 (assuming manual disassembly and contaminant content higher than 1% in mass). - Contamination regards penalty elements as in Table 10 (assuming manual disassembly and contaminant content higher than 1% in mass). - Contamination is due to the use of shredders for the separation/disassembly.
Low	25%	75%	- Contamination regards the use of acoustical foam, metal inserts, paints, brackets, coatings, labels, glues or adhesives (contaminant content higher than 1% of the component mass), unless manufacturer/designer can prove with a sufficient technical/scientific documentation that that employed materials are compatible with the recycling or/and contaminant can be removed without residues in an economic viable way.
None	0%	100%	- none of the previous situations

[36] The table is only illustrative of the proposed methodology. The reported values are not representative of the effective disassembly process.

Table 12 Example of table for the calculation of 'Contamination index' for recoverability[37]

To what extent the contamination affect the *Recoverability* of the materials?			
	C_2	**C_2'**	Note
High	100%	0%	- Contamination regards hazardous substances regulated by the RoHS Directive and substances classified as 'Substance of Very High Concern (SVHC)' by the REACH Directive (contaminant content higher than 0.1% of the component mass);
Medium	50%	50%	- Contamination regards substances and compounds (as below reported in the note) that, if incinerated, could generate the release of toxic compounds (contaminant content higher than 1% of the component mass). - Contamination due to separation of the material by shredding.
None	0%	100%	- none of the previous situations

Note - Substances and compounds should not be incinerated if containing Thallium[38], Gallium, Osmium, Selenium, Arsenic, PVC[39], Glass reinforced plastics[40].

2.5.3.1 Verification procedure for the contamination index

The 'contamination index' is calculated by the manufacturer as an intermediate step for the calculation of the RRR indices. The verification of the 'contamination index' is therefore part of the verification process of the RRR indices, based on self-declaration of the manufacturers supported by technical documentation.

Examples of documentation to be provided are:

- The BOM and further technical documentation concerning the design plans to prove that no quantitatively relevant contaminations among materials occur;
- If contaminations occur, their incidence needs to be calculated based on the mentioned tables 11 and 12. Discrepancies from these values could be possible if the designer/manufacturer provides sufficient technical/scientific documentation and a detailed discussion to support their assessment. In particular, designer/manufacturer should prove that an identified contamination (due e.g. to labels, inks or painting) do not preclude or make economically not viable the recycling/recovery[41].

[37] The table is only illustrative of the proposed methodology. The reported values are not representative of the effective disassembly process.

[38] Waste materials that contain mercury, thallium, gallium, osmium, selenium, or arsenic should not be incinerated because volatile, toxic combustion products may be emitted [NRC, 1995].

[39] Baitz et al. 2004 underline that the presence of PVC in municipal solid waste has a direct effect on the quantity of chlorine in the raw gas and therefore on the corresponding gas treatment required. The higher chlorine content in the gas requires additional neutralisation agent supply and therefore affects the quantity of residues or effluents generated by the different gas-treatment systems (dry, semi-dry and wet). The content of PVC also contributes to the emission of dioxins and heavy metals [Baitz et al. 2004]. The study concludes that there are benefits of diverting PVC away from incineration. Recycling is determined to be better than disposal, but it is also acknowledged that not all PVC can be recycled. Furthermore, it is noted that the disposal in landfill of PVC comes out positive, because the leaching of additives such as phthalates is weighted as a less serious environmental problem than emissions from incineration.

[40] Some authors arise doubts about the incineration of glass reinforced plastics. This is often problematic (due to glass fibers that cannot be incinerated neither at very high temperature) and very expensive compared to other disposal treatments [Lee et al., 2008]. The heat content of glass reinforced plastics comes from the organic materials in the resin (generally 25% - 30%): its heat content is low while its ash content is high.

[41] For example some companies developed a fully recycling compatible label for plastics as ABS, PC and HIPS and their blends. This type of product is designed to be recycling compatible and not influence physical and mechanical properties of the recycled feedstock [Siioss Et Al., 1999].

2.5.4 An index for the material degradation

The physical and chemical characteristics of the materials play an important role concerning the recyclability and reusability.

As discussed in Deliverable 1, some materials (as metals) can be 'theoretically' always recycled, conserving more or less their initial properties over the time. After the recycling, these materials can therefore replace virgin materials in the production processes.

Other materials (e.g. plastics or paper) are affected, after the use and the recycling, by structural changes that modify and reduce their potential for the recycling. Actually, these materials cannot completely substitute virgin materials but they can be a partial substitute or be used for 'lower level' productions, meaning productions where a lower quality of input materials is needed.

Analogously, the reusability of a component is related to their use stage and to their collection at the EoL. In fact*, reusable parts are characterized by a limited number of reuse cycles before their disposal*. A preliminary check of reusable parts is always performed by manufacturers in order to verify if the component is still suitable for the reuse/remanufacture.

<u>It can be synthesized that the degradation and change in the inherent properties of the materials influences the material recyclability[42]; while the wear/deformation of a component can compromise his reusability</u>. On the other side, the material degradation does not relevantly affect the potential energy recoverability (that is mainly related to the chemical nature of the materials and their calorific values).

Due to the different influence of the material degradation on the measurement of the reusability and recyclability, two different factors are introduced.

2.5.4.1 Material degradation 'M_D' index for the reusability

The material degradation influences the reusability in so far as worn-out parts cannot accomplish anymore to their initial scope. On such purpose, the manufacturer should estimate the percentage of components that are reusable after their EoL.

The 'Material Degradation' index "$\mathbf{M_D}$" estimated *the attitude (measured as percentage [%]) of the product/component to be suitable for the reuse after its operational time.*

$\mathbf{M_D}$ represents the percentage of new-manufactured products/components that can be reused. The remaining share (1- $\mathbf{M_D}$) represents the percentage of products/components that are worn-out/damaged and no more suitable for reuse. Higher values of the $\mathbf{M_D}$ are related to products/components that have a lower probability to be damaged or worn-out.

The estimation of $\mathbf{M_D}$ has to be supported by a 'prediction/estimation' of the product/component use. In particular, manufactures should estimate the value of $\mathbf{M_D}$ on the basis of:

[42] For more detail see Deliverable 1 - Chapter 2.2.1

- Expected physical/chemical stress and wear that the component could suffer;
- Literature data about returned components or experimental data (for example, from prototypes testing) about the suitability of the component for the reuse;
- Criticality of the component functions (in relation also to technical standards and legislative requirements);

For example the assumption M_D = 80% means that, on average, every 100 new-manufactured pieces, 80 will be potentially reusable, while 20 pieces are not suitable for a second-use cycle.

The M_D index for a component can be calculated as:

Formula 13 $$M_D = M_{D,1} \cdot M_{D,2} \cdot M_{D,3}$$

Where:

- M_D = Material Degradation index for the measurement of reusability of the component [%];
- $M_{D,1}$ = Material Degradation 'sub-index' (expressed as percentage of the component [%]) related to the 'criticality for reuse'. It is related to the presence of technical standards and laws that regulate the use of the product/components and concerning (e.g. concerning safety or hygienic requirements). It is assumed that critical components should pass strict quality checks before the reuse and this would reduce their chances to be reused[43];
- $M_{D,2}$ = Material Degradation 'sub-index' (expressed as percentage of the component [%]) related to the 'physical-chemical stress'. Products and component that are subjected to high stress (e.g. mechanical tensions, thermal variations, frictions or scraping) would probably be more damaged/consumed. Therefore they have a lower chance to be reused or would require a prolonged refurbishment before the reuse;
- $M_{D,3}$ = Material Degradation 'sub-index' (expressed as percentage of the component [%]) related to the probability that an incorrect use by users could compromise the functionalities of the product/component. Designer/manufacturer has to predict/estimate the possibilities that the product/component would be returned damaged after the use and no more suitable for reuse. For example, internal shielded components (or fixed components) have lower probability to be damaged than external (or mobile) ones.

The material degradation sub-indices can be estimated by means of Figure 8. Values here reported are only illustrative. More detailed tables could be drawn in cooperation with stakeholders.

[43] Note that a similar check is also requested by the standard ISO 22628 concerning the reusability of components for vehicles. In particular, the standard states that: "the reusability of a component part shall be subject to consideration of safety and environmental hazards".

It is recognized that the estimation of the material degradation index for reuse is based on subjective assumptions. Such assumption should, however, be supported considerations/scenarios about the EoL of the products. Here again we underline the differences among the measurement of the reusability (as 'potential') and the assessment of the effective 'reuse' (that is instead affected by several factors related to the behaviour of the users and the EoL collection and treatments).

The $\mathbf{M_D}$ index should be here estimated on the basis of plausible assumptions that have to be supported by sufficient detailed data, plans, software and literature examples.

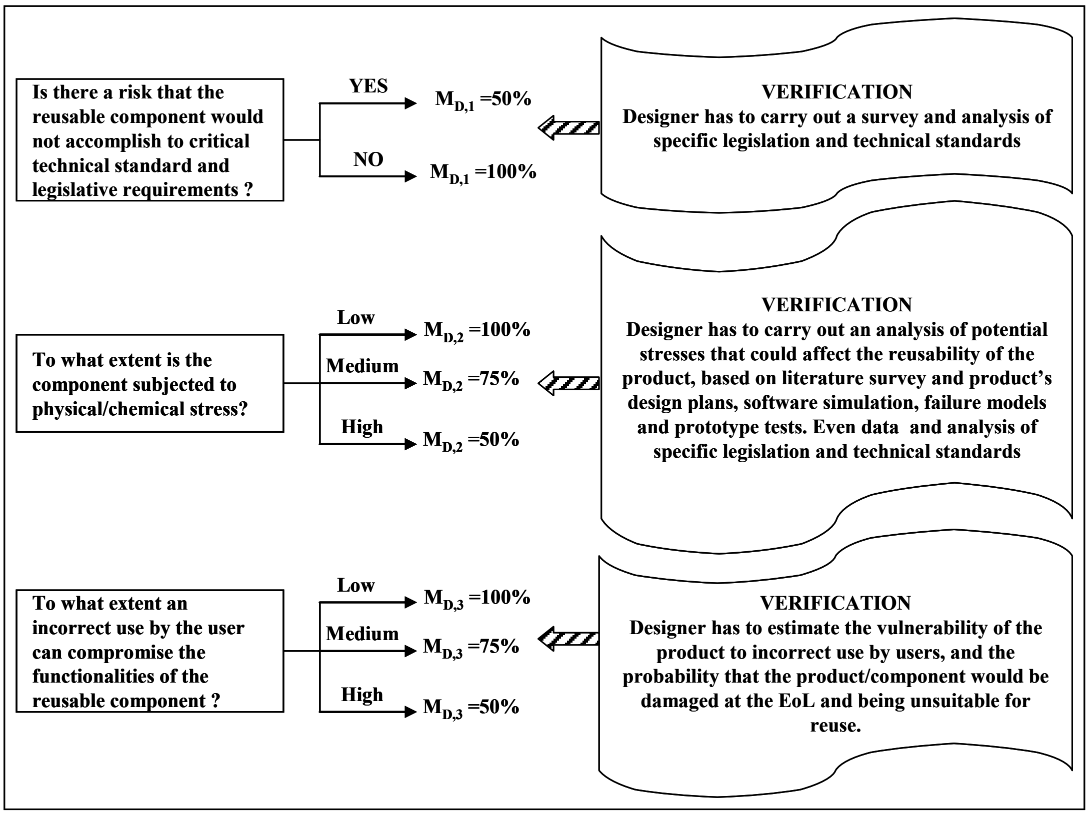

Figure 8 Procedure to assess the materials' Degradation sub-indices $M_{D,1}$, $M_{D,2}$ and $M_{D,3}$ [44]

It is also possible that manufacturers would use different values from those reported in the previous scheme. Deviations have, however, to be detailed, motivated and supported by adequate additional experimental and/or literature data. For example, the designers could declare and describe if specific design solutions have been adopted to avoid the incorrect use by the users or to mitigate the wear, increasing the probability for the reuse.

[44] The values of the M_D index in the present figure are only illustrative.

2.5.4.1.1 Limits in the methodology for the calculation of the material degradation M_D and potential alternative approaches

The previously described methodology and the procedure for the calculation of the material degradation index 'M_D' is based on a self-assessment of the manufacturers. They have to assess to what extent the designed components are suitable for the reuse and the potential risks of degradation including also the potential incorrect use by the users.

Although detailed and comprehensive, this approach is affected by large uncertainties related to assumptions of the manufacturer during the assessment of the degradation index.

Possible alternative approaches include:

- To define some tables with prefixed values of the degradation index MD for the considered specific product category
- To stop the assessment of the degradation index to the first step of previous methodology in Figure 8. It means that the value of the M_D index is set to fixed value (e.g. 50%) whenever the component has to accomplish to some specific requirements regulated by e.g. safety or environmental regulations.

2.5.4.1.2 Verification of the material degradation index M_D

The 'material degradation' index for the measurement of the reusability is calculated by the manufacturer as an intermediate step for the calculation of the RRR indices. The verification of the ''material degradation' index for the measurement of the reusability is therefore part of the whole verification process of the RRR indices, based on self-declaration of the manufacturers supported by technical documentation.

Examples of documentation to be provided are:

- The assessment of the product/component criticality based on technical standards and legislative requirements in force;
- The assessment of the wear that could affect the product/component during its operating time. The assessment should be based on the identification, modelling and assessment of potential physical/chemical stress that could affect the functionality of the product/component. Data can be based on direct experimentations/testing or literature data;
- Prediction and assessment of the potential damages caused by the use (including assumptions about the potential incorrect use of the product). Data can be based on direct experience of the designer/manufacturer or literature data.

2.5.4.2 Material recyclability ‘M_R’ for the measurement of the recyclability of products

As above mentioned, the material degradation is a key issue of the recyclability of materials. In fact, the change of inherent properties of materials after the EoL treatments can significantly affect their potential for recycling.

Several plastics after the recycling are only suitable for ‘lower quality’ applications. For example, virgin Polypropylene (PP) fibres have good chemical and mechanical resistance that allow their use in several high-resistant components (e.g. cars bumpers). PP can be also easily recycled but, due to the chemical changes during the recycling, secondary fibres are generally used for applications that require a lower tensile strength (e.g. the manufacture of furniture or toys).

The assessment of the material degradation is, however, a very complex task, including physical, chemical, technical, technological and economic matters. It also depends on the use of the product during its operational life, and on the activities at the product’s EoL. Therefore material degradation for recycling is generally indirectly estimated, considering some related factors.

For example, it was observed that to take into account the changes of properties and material degradation, a “*value correction*” approach could be applied, e.g. by using the market-price ratio between the secondary good and the primary material [EC, 2010b].

This concept has also been presented in the scientific literature, where economic indices have been used to figure out complex situations, as the material recyclability. One of the most consolidated indices about the recyclability of materials is the ‘Material Recyclability’ - $\boldsymbol{M_R}$[45], defined as *the ratio between the value of recycled material and the value of the virgin material* [Villalba et al., 2002]. In formula:

Formula 14 $$M_R = \frac{V_P}{V_M}$$

Where:

- V_M = Minimum value of a material (€/kg or \$/kg). This is the minimum value of the material before being treated or shaped for a specific use (i.e. metals in ingots, polymers in granules);
- V_P = Post-recycle value of a material (€/kg or \$/kg). This is the value that a given material has after it has been recycled and is ready for its second use, before being treated or shaped for a specific use.

The price paid for scrap materials is a measure of their environmental value as recyclables. The value reflects several different aspects and properties of materials (physical, technical,

[45] In Villalba et al, 2002, the ratio is named “*Recycling index* - *R*”. For more detail about the index see Deliverable 1 – Chapter 2.3.1

technological, economic, environmental and social driving forces) and it can provide relevant information about the effectiveness with which resources are reclaimed and returned to productive use

Economic variables can be also influenced by situation not directly related to the technological recyclability of a material (e.g. geopolitical situations, international markets, economic speculations). It was however observed that “*as the international steel market goes, so goes the demand for scrap*”. In fact, “*the price of secondary materials (waste materials) is highly influenced by the price of raw materials and thus by the overall economic development*”[46].

This implies that scrap and virgin material prices decrease or increase in a related way and this causes a generally almost constant value of the ratio ‘M_R’.

For example, Figure 9 reports the values of M_R for some metals over one decade, showing an almost constant trend [Villalba et al., 2002].

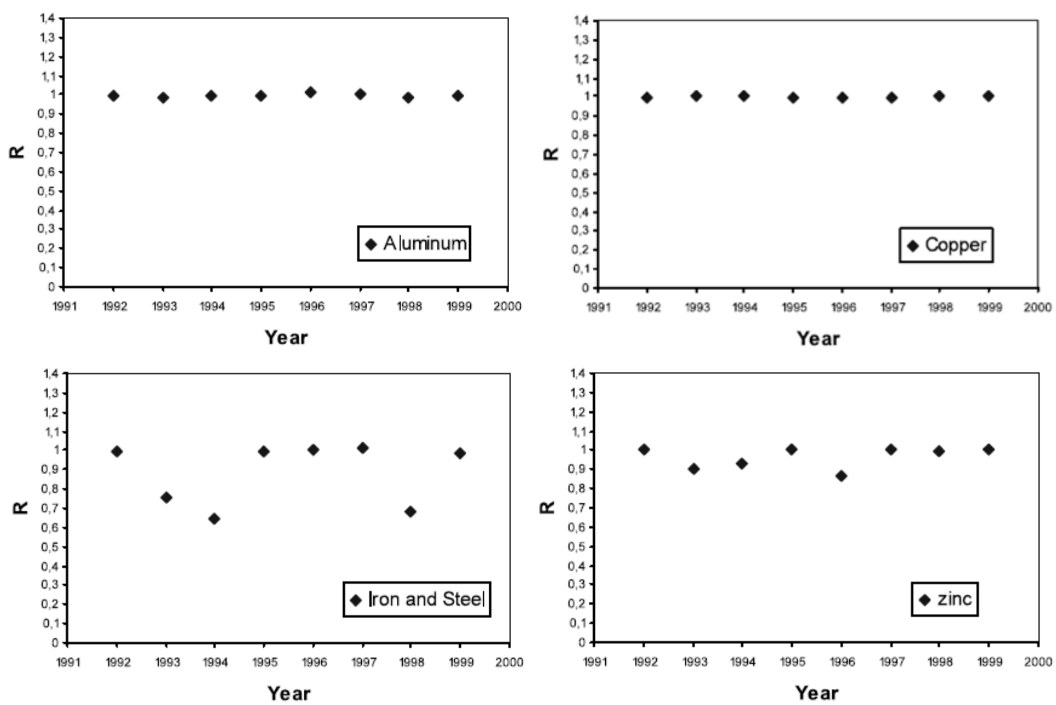

Figure 9 Variation of the index ‘M_R’ over the time for some exemplary metals [Villalba et al., 2002]

Values of the M_R index have been calculated for various materials (see Annex 1). In particular, data about metals show very high values of the index, generally close to 1. The only exception is represented by stainless steel characterized by low prices of the scraps compared to the virgin material. However, the market of recycled stainless steel is largely

[46] Eurostat, from: http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastemanagement/recycling

growing and, as observed by some authors, stainless steel is characterized by high recyclability and it maintains its physical/chemical properties after recycling [Reck et al., 2010].

Concerning plastics, the recycling involves mainly thermoplastics, and to a lower extent also elastomers and thermoset plastics.

For thermoplastics, the recycling process consists of "*grinding the plastics into pellet-sized fragments and using those fragments as the input stream for injection moulding, extrusion, or film casting operations. Plastics unsuitable for these processes because of additives or colorants can undergo open-loop recycling to park benches and other secondary uses*" [Graedel and Howard-Grenville, 2005].

Recycling concerns mainly some polymers[47]: PET, PE-HD, PVC, PE-LD, PP, PS, PC, ABS. Values of M_R of these plastics have been calculated in Annex 1. The index moves in the range of 0.65 – 0.85.

Recyclability of thermoset plastics and elastomers is restricted and mostly limited to the use of grinded plastic scraps as filler for new plastics [Pickering, 2006]. Few data were instead available concerning the paper/cardboard and glass.

Glass, for example, can be used for high precision medical tools when virgin. In this case, "*recycled glass, with today's recycling technology, is used in glass containers and glasphalt (for highway construction). Its second application is of less value because recycled glass does not have the same properties (i.e. colour, thermal properties) as virgin glass. If glass were truly recyclable, it could be used once again to make the medical tool. Glass, therefore, has a low recycling index although it has high reusability*" [Villalba et al., 2002]. This applies however only if the primary glass has high purity. For e.g. container glass, having the highest mass share, the recycling index is high, and again highest for brown or green glass, somewhat lower for white glass, depending on the degree of whiteness. Flat glass is in between.

Values of the M_R index has to be pre-calculated and continuously updated, taking also into account the technological progress in the recycling/sorting technologies Table 13 shows an example of average M_R values that have been calculated on the basis of data of survey of Annex 1. These values can be assumed as illustrative for the purposes of study.

[47] These are the main resins that were identified as recyclable by the Society of the Plastics Industry. A specific coding system has been developed for them, in order to facilitate their identification and recycling (from: http://www.plasticsindustry.org/AboutPlastics/content.cfm?ItemNumber=825&navItemNumber=1124 ; December 2010).

Table 13 Values of the index ‘M_R’ of some materials[48]

Material	M_R index
Metals (*)	1
ABS (****)	0.84
Polycarbonate (****)	0.77
PE-HD (**)	0.85
PE-LD (***)	0.71
PET (**)	0.68
PP (****)	0.81
PS (***)	0.86
PVC (****)	0.76
Paper[49] (**)	0.16
Glass (**)	0.75

(*) estimated from http://minerals.usgs.gov/minerals
(**) from [Villalba et al, 2002]
(***) from [Rader and Stocker, 1995]
(****) estimated from http://plasticsnews.com

Note that the M_R index does not take into account mass losses during the recycling process. However this material loss can represent an additional ‘key issue’ for the measurement of the recyclability, and it could be added in the future to the current methodology.

2.5.4.2.1 Limits on the methodology for the calculation of the M_R index

The previous methodology for the calculation of the M_R index is affected by some uncertainties and limits, as follows:

- the degradation of physical/ chemical properties of recycled materials is indirectly estimated by the loss of the economic value;
- the economic values can fluctuate due to market reasons that are not related to the recycling process
- it has been observed a limited availability of data concerning the value of post-consumer recycled materials, which are representative for the European context.

An alternative approach for the calculation of the M_R index is therefore proposed.

It is assumed that the M_R index could only have two values:

- ($M_R = 0$): if the material is not recyclable;
- ($M_R = 1$): if the material is recyclable.

It is assumed that a material is recyclable if exists a technology economically viable for the recycling. For example, it can be assumed that a material is recyclable if there are in Europe at least two facilities for the recycling [Mathieux et al., 2008].

[48] The values of the table are only illustrative of the proposed methodology.

[49] The data refers to generic ‘paper’ without any further detail. In the next section, this value of the M_R index will be also extended to cardboard.

2.5.4.2.2 Verification procedure for the material recyclability index

The material recyclability index is calculated by the manufacturer as an intermediate step for the calculation of the RRR indices. The verification of the material recyclability index is therefore part of the whole verification process of the RRR indices, based on self-declaration of the manufacturers verified e.g. by a Market Surveillance Authority. This Authority has therefore to check that the manufacturer correctly and consistently used the pre-calculated tables (as those in Table 13) in the 'calculation data sheet' for the RRR indices.

2.5.5 Parameters of the methodology and technology mix

The previous chapters introduced the methodology for the measurement of the *RRR* potentials. In particular the following factors have been introduced / discussed:

- the Disassemblability of the product/components,
- the contamination among the materials and
- the degradation of the materials due to their use and/or recycling.

These factors are related to the availability and efficiency of the employed technologies.

However, it has been pointed out several times that the measurement of the *RRR* takes place at the Design stage, and this measurement is not related to the 'real' EoL of the product. In fact, it is not possible to foresee how and where the product will be at the EoL and what treatments it will undergo. Therefore it is necessary that the proposed methodology would refer to an average European scenario, considering an average technological level.

The technological assumptions introduced up to here concern:

a) <u>*Disassemblability* by mechanical shredding ('Disassemblability' index 'D')</u>.

Table 6 introduced some average values of efficiency of shredders for different material typology. These values are then used to calculate the disassemblability of components that cannot be separated manually.

Values of Table 6 refer to average separation rates described in the scientific literature. These values can be considered also as representative for the European technological context. It has been however observed that the efficiency of shredders grew up in the last decade and it is possible that this efficiency could be further improved in the future. In particular, Table 6 assumed that separation of plastics from shredders is not suitable for recycling but only for recovery.

Actually the scientific literature describes some shredders that are able to separate also efficiently some plastics (e.g. by gravity separation) that are addressed to the recycling (e.g. the separation of plastics from copper into electrical wires).

Note that however, the efficiency of the shredders is strongly related to the 'quality' of the input waste. The residual of unsorted waste is, however, generally not suitable for recycling. The value of Table 6 can be therefore considered as ‘precautionary’, also with the scope to promote, with the methodology, the manual disassembly.

A *procedure* to define/update the values of the mechanical efficiency of shredding is:

- Survey of the scientific literature and technical manuals to identify declared/measured values of the efficiency of shredding technologies (related to treated waste input, and desired outputs[50]);
- Identification of the technology/ies more representative for the European context (e.g. those that are largely used in the EU in terms of number of plants or quantity of treated waste);
- Define/revise average shredding efficiency values for different materials (Table 6).

The manual disassembly does not refer to technological mix, but to some thresholds of feasibility (related to the time necessary to disassemble). Values of Table 7 are illustrative of the methodology. However, different thresholds for the calculation of the manual disassembly could be fixed on the basis of the stakeholder experience.

b) *Contamination* among materials (Contamination indices ‘C_1’ and ‘C_2’).

Contamination has been discussed in Chapter 2.5.3. It aims at identifying those sources of contaminations that can interfere with recycling/recovery. This parameter is strongly related to the technology variations and sensible differences can be observed over the time.

The scientific survey revealed some examples of incompatibilities (e.g. Table 9 and Table 10), but the list could be further enlarged, including also other materials, and updated periodically on the base of the technological progress. The values reported in Table 11 and Table 12, have been built on the outcomes of the survey on EuP and the results of the examples/case-studies discussed in the present report.

However, the values of Table 11 and Table 12 need to be discussed, involving also stakeholders, and potentially adapted to case-by-case considerations related to the considered product category.

A feasible *procedure* for the definition/updating of the contamination values is:

- Survey of the scientific literature and interview of stakeholder to indentify possible sources of contamination among the materials that can interfere with EoL treatment of the product/component;
- Qualitative/quantitative assessment of how much the contaminant can influence the recycling/recovery (producing diagrams similar to those of Table

[50] The efficiency of the shredders can be, in fact, set to optimize the separation of one or more materials (e.g. the separation of precious metal from electronic waste).

9 and Table 10). In particular the assessment should identify the thresholds over which substances/materials and other contaminants (glues, adhesives, paints, solders, etc.) can make the component no more suitable for the recycling/recovery;

- Define/revise average contamination rate for the different contamination indices (Table 11 and Table 12).

c) *Material degradation (Material Recyclability index 'MR').*

Material Recyclability is a parameter that affects the recyclability of a product/component. This parameter is strongly related to economic and technological data. As in detail explained in Chapter 2.5.4.2, the index *'MR'* has been introduced to estimate the recyclability based on the economic value of the virgin/recycled materials.

The presence of the economic values makes the index *'MR'* sensible to market changes. Economic variables can be also influenced by situation not directly related to the technological recyclability of a material (e.g. geopolitical situations, international markets, economic speculations). It was however observed that (Chapter 2.5.4.2) "*the price of secondary materials (waste materials) is highly influenced by the price of raw materials and thus by the overall economic development*". This implies that scrap and virgin material prices decrease or increase in a related way and this causes a generally constant trend of the index 'M_R'.

Values of M_R have to be calculated for each material and regularly updated.

An exemplary procedure for the calculation of M_R has been described in Chapter 2.5.4.2.2. The procedure is here pointed out:

- It is necessary to establish if the material is recyclable (i.e. the recycling is technologically feasible and economically practicable). The suitable recycling technologies have to be identified/described;
- European market data (referring to at least one year base[51]) have to be collected concerning the average values of virgin/recycled material.
- The value of the M_R index is calculated as in Formula 14.

Table 13 reports some exemplary values of the M_R index of some materials commonly used for the manufacturing of EuP. These have been calculated on the basis of data of survey of Annex 1 (including European and extra-EU references). These values should be assumed only as illustrative for the proposed methodology.

[51] Average data on a longer time span are preferable, because could avoid price distortions due to non-technological matters.

2.6 Integration of previous indices with the product's BOM

As described in Chapter 2.4, the estimation of the 'Reusability Ratio', 'Recyclability Ratio' and 'Recoverability Ratio', is based on the calculation of the values of the 'm_{reuse}' , '$m_{recycle}$' and '$m_{recover}$' for each product's component, by the formulas of Chapter 2.5.

The calculation of the *RRR* indices is therefore based on the integration of information of the BOM with the previous assumptions about materials 'disassemblability', contamination and degradation. In order to facilitate the calculation, an exemplary spreadsheet has been realized (Table 14).

Table 14 Example of spreadsheet for the calculation of the Reusability Ratio 'R_{Reuse}', Recyclability Ratio '$R_{Recycle}$', the Energy Recoverability ratio '$ER_{recovery}$' and the Recoverability Ratio '$R_{Recovery}$'.

Component		Details			Reusability			Recyclability				Recoverability			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{E\text{-}recovery}$	($m_{recycle}$ + $m_{E\text{-}recovery}$)
		Total mass "m_{tot}" [kg]			Σ m_{reuse} [kg] **R_{Reuse} [%]**			Σ $m_{recycle}$ [kg] **$R_{Recycle}$ [%]**				Σ $m_{E\text{-}recovery}$ [kg] **$ER_{Recovery}$ [%]** Σ ($m_{recycle}$ + $m_{E\text{-}recovery}$) **$R_{Recovery}$ [%]**			

Concerning the **Reusability Ratio 'R_{Reuse}'** the calculation involves only those components (m_i) that were specifically designed to be reused/remanufactured; not reusable components have a value of $m_{reuse} = 0$.

Concerning the **Recyclability Ratio '$R_{Recycle}$'** the calculation includes those components and materials "m_i" that are technologically and economically suitable for recycling. Not recyclable components have a value of $m_{recycle} = 0$.

Concerning the **Energy Recoverability Ratio** '$ER_{Recovery}$' the calculation includes those components and materials "m_i" that have the energy content (feedstock) potentially recoverable.

The **Recoverability Ratio '$R_{Recovery}$'** includes, instead, both the materials that are energy recoverable and those that can be recycled.

2.6.1 Verification of the RRR indices calculation

The verification of the RRR indices is based on self-declarations supported by technical documentation available before the product is put into the market and provided on request.

The declarations could be verified e.g. by a Market Surveillance Authority (MSA) that can check the truthfulness of provided information and successively would follow the calculation done by the manufacturer in the 'calculation data sheet'.

The provided documentation could include:

- the BOM (Chapter 1.3.3);
- the documentation for the calculation of the 'disassemblability' (Chapter 2.5.2.3);
- the documentation for the calculation of the material contamination (Chapter 2.5.3.1);
- the documentation for the calculation of the material degradation for reuse (Chapters 2.5.4.1.1

2.7 Calculation of the combined 'Reusability/Recyclability' and 'Reusability/Recoverability' indices

Some directives introduced requirements for products concerning *reusability/recyclability* together or concerning *reusability/recoverability* together.

For example, the "Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability" [EU, 2005] establishes that:

"*Vehicles [...] shall be so constructed as to be:*

— reusable and/or recyclable to a minimum of 85 % by mass, and

— reusable and/or recoverable to a minimum of 95 % by mass"

However the indices defined in Chapter 2.4 cannot be simply summed; otherwise some materials could be double-counted resulting to an overall value of the index bigger than 100%.

Two new combined indices are therefore introduced: the '*Reusability/Recyclability*' and the '*Reusability/Recoverability*'.

'**Reusability/Recyclability**' (***$R_{ReuseRecycle}$***) [%]: it is the percentage (in mass) of the product that is potentially reusable and recyclable. It is calculated as:

Formula 15 $$R_{ReuseRecycle} = \frac{\sum_i \sum_k m_{reuse/recycle_{i,k}}}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{reuse/recycle,i,k} = m_{reuse,i,k} + m_{recycle,i,k}$ [kg] (calculated with formulas 6 and 7);

<u>note</u>: IF: ($m_{reuse,i,k} + m_{recycle,i,k} > m_{i,k}$) $\Rightarrow$ THEN: ($m_{reuse,i,k} + m_{recycle,i,k} = m_{i,k}$);

ELSE: ($m_{reuse/recycle,i,k} = m_{reuse,i,k} + m_{recycle,i,k}$)

‘**Reusability/Recoverability**’ ($\boldsymbol{R_{ReuseRecovery}}$) [%]: it is the percentage (in mass) of the product that is potentially reusable and recoverable. It is calculated as:

$$\textbf{\textit{Formula 16}} \quad R_{ReuseRecovery} = \frac{\sum_i \sum_k m_{reuse/recovery_{i,k}}}{m_{tot}} \cdot 100$$

- m_{tot} = total mass of the product [kg];
- $m_{reuse/recovery,i,k} = m_{reuse,i,k} + m_{recycle,i,k} + m_{E\text{-}recovery,i,k}$ (calculated with formulas 6, 7, 8);

note: IF: ($m_{reuse,i,k} + m_{recycle,i,k} + m_{E\text{-}recovery,i,k} > m_{i,k}$) ⇒

THEN: ($m_{reuse,i,k} + m_{recycle,i,k} + m_{E\text{-}recovery,i,k} > m_{i,k}$);

ELSE: ($m_{reuse/recovery,i,k} = m_{reuse,i,k} + m_{recycle,i,k} + m_{E\text{-}recovery,i,k}$)

The calculation and verification of these new indices is similar to that already defined for the previous *RRR* indices. It is important to note that reusable parts can also contribute to the recyclability and/or to the recoverability of the products. In any case, a component cannot contribute to the indices for more than 100% of its mass.

Analogously to formula 4 in Chapter 2.4.1.1, two physical constraints have been here added as described in the notes of the previous formulas 15 and 16.

2.7.1 Calculation of the combined Reusability/Recyclability' and 'Reusability/Recoverability' indices

The calculation of the 'Reusability/Recyclability' and of the 'Reusability/Recoverability' indices can be performed by means of the new calculation spreadsheet, as shown in Table 15.

Table 15 Spreadsheet for the calculation of the 'Reusability/Recyclability' Ratio and of the 'Reusability/Recoverability' Ratio.

Component		**Details**			**Reusability**			**Recyclability**				**Recoverability**				**Reusability-recyclability**	**Reusability-recoverability**
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{rE\text{-}recovery}$	$(m_{recycle} + m_{E\text{-}recovery})$	$m_{reuse/recycle}$	$m_{reuse/recovery}$
												$\Sigma m_{E\text{-}recovery}$ [kg] **$ER_{Recovery}$ [%]**					
		Total mass "m_{tot}" [kg]			Σm_{reuse} [kg] **R_{Reuse} [%]**			$\Sigma m_{recycle}$ [kg] **$R_{Recycle}$ [%]**				$\Sigma m_{recovery}$ [kg] **$R_{Recovery}$ [%]**					
												$\Sigma m_{reuse/recycle}$ [kg]					
												$R_{Reuse/Recycle}$ [%]					
												$\Sigma m_{reuse/recovery}$ [kg]					
												$R_{Reuse/Recovery}$ [%]					

2.8 Calculation of the *RRR*: an illustrative case study

This paragraph will present an example for the calculation of the three introduced indices ('*Reusability Ratio', 'Recyclability Ratio' and 'Recoverability Ratio')* applied to the illustrative example of the coffee-maker of Chapter 1.4.

The starting point for all the successive estimations is represented by the BOM. Figure 10 shows a synthesis of the disassembly scheme with the inclusion of the time for the disassembly.

Concerning the detail of the materials, we refer to data of Table 3. Concerning the detail of the disassembly steps, we refer to data of Table 4.

All the above mentioned information been then applied to the calculation spreadsheet of Chapter 2.6. Results are presented in Table 16.

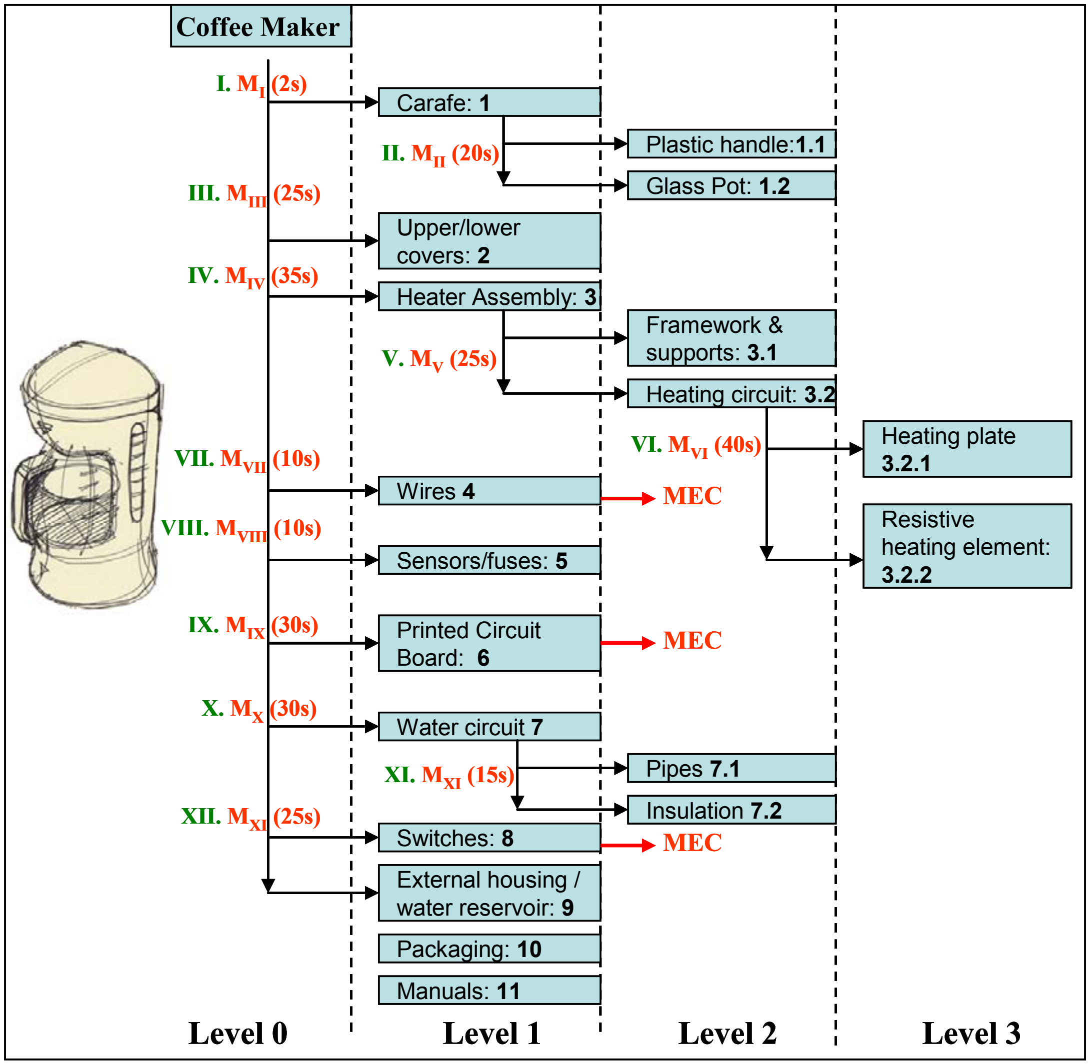

Figure 10 **BOM of a coffee-maker**

Table 16 Example: calculation of the Reusability Ratio 'R_{Reuse}', Recyclability Ratio '$R_{Recycle}$' and Recoverability Ratio '$R_{Recovery}$' of a coffee-maker

Component		Details			Reusability			Recyclability				Recoverability			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{E\text{-}recovery}$	($m_{recycle} + m_{E\text{-}recovery}$)
Plastic handle	1.1	Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl	0.05	100%	56.3%	0.03	98%	100%	77%	0.04	98%	100%	0.05	0.05
Glass pot	1.2	Glass	Borosilicate heat resistant glass: Boron (B) content: 4%	0.5	100%	25%	0.13	98%	0%	75%	0				0
		Steel	Screws	0.01	100%	100%	0.01	98%	100%	100%	0.01				0.01
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A (0.05%)	0.05				98%	100%	84%	0.04	98%	100%	0.05	0.05
Framework /supports	3.1	Steel		0.08				84%	100%	100%	0.07				0.07
		Steel	Screws	0.01				84%	100%	100%	0.01				0.01
Metal heating plate	3.2.1	Copper		0.1				72%	100%	100%	0.07				0.07
		Steel	Screws	0.04				72%	100%	100%	0.03				0.03
Resistive heating element	3.2.2	Copper		0.06				72%	100%	100%	0.04				0.04
Wires	4	Copper		0.075				71%	50%	100%	0.03				0.03
		Polypropylene (PP)	Combustible-LHV:46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.025				0%	50%	81%	0	42%	50%	0.01	0.01
Sensors/ fuses	5	Various (metals, glass)		0.02											0
Printed Circuit Board	6	Copper		0.03				68%	50%	100%	0.01				0.01
		Steel		0.02				76%	50%	100%	0.01				0.01
		Aluminum		0.04				72%	50%	100%	0.01				0.01
		Glass-reinforced plastic	Potential combustible but with low feedstock content	0.03				0%	50%	0%	0	40%	50%	0.01	0.01
		Other		0.01				0%	50%	0%	0				0
		Steel	Screws	0.01				76%	100%	100%	0.01				0.01
Pipes	7.1	Aluminum		0.6				66%	100%	100%	0.40				0.40
Insulations	7.2	Polypropylene (PP)	Combustible - LHV: 46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.05				66%	100%	81%	0.03	66%	100%	0.03	0.05
Switches	8	Copper		0.01				56%	50%	100%	0.003				0.003
		Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.04				0%	50%	77%	0	33%	50%	0.01	0.01
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A(0.05%); Painted and labeled parts (contaminant content >1%).	0.3				66%	75%	84%	0.12	66%	100%	0.20	0.30
Packaging	10	Low Density Polyethylene (PE-LD)	Combustible - LHV: 42 MJ/kg; Flame ret.: Red Phosphorus	0.01				100%	100%	71%	0.01	100%	100%	0.01	0.01
		Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg	0.4				100%	100%	16%	0.06	100%	100%	0.40	0.40
User's Manuals	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.03				100%	100%	16%	0.005	100%	100%	0.03	0.03
												$\Sigma m_{E\text{-}recovery}$		0.79	
												$ER_{Recovery}$		**30.3%**	
		Total mass "m_{tot}" [kg]		2.6		Σm_{reuse} [kg]	0.16			$\Sigma m_{recycle}$ [kg]	1.00			$\Sigma m_{recovery}$ [kg]	1.60
						R_{Reuse} [%]	**6.3%**			**$R_{Recycle}$ [%]**	**38.5%**			**$R_{Recovery}$ [%]**	**61.6%**

2.8.1 Calculation of the 'Reusability Ratio'

The first step is represented by the calculation of the '*Reusability Ratio'*. It concerns only those components (if present) that were specifically designed for reuse/remanufacturing.

On such purpose, it is assumed that the designer of the coffee-maker claims the reusability of the carafe (embodying the plastic handle, the glass pot and the screws). The carafe can be reused for new coffee-machines and can be reinserted into the production process after minor treatments (quality check and cleaning). A quality check is performed before the remanufacturing of the carafe to identify possible damages that could compromise the reuse.

Other parts (i.e. the external/internal frameworks, the heating circuit and other electrical/electronic components) cannot be reused because of their wear during the use stage.

The calculation spreadsheet of the reusability ratio is showed in Table 16. It is estimated that:

- the disassembly index 'D' is 100% for all the carafe components, being the component specifically designed to be suitable for reuse (Chapter 2.5.2.1);
- the material degradation index is :
    - (Plastic Handle) M_D = 100% · 75% · 75%= 56.3% (from formula 12: M_{D1} = 100% considering that there are not critical legislations/standards concerning the component; M_{D2} = 75% because the component is external and subjected to wear; M_{D3} =75% because there is a medium risk that that an incorrect use by users could compromise the functionalities of the component by, for example bumping or scratching it);
    - (glass carafe) M_D = 100% · 50% · 50%= 25% (from formula 12: M_{D1} =100% considering that there are not critical legislation/standard concerning the component; M_{D2} =50% because the component is extremely subject to wear due to the thermal stress that it has to suffer; M_{D3} =50% because the component is continuously handled by the user with high risks to crash or scratch it);
    - (screws) M_D = 100% · 100% · 100%= 100% (from formula 12: M_{D1} =100% considering that there are not critical legislation/standard concerning the component; M_{D2} =100% because the component is not subject to particular wear; M_{D3} =100% because there is a low/null risk that that an incorrect use by users could compromise the functionalities of the component).

The Reusability Ratio of the coffee-maker results 6.3% in mass.

In order to allow the **verification** of the estimated values, the designer should provide the following documentation:

- BOM, with the detail of material breakdown and the timing for disassembly;
- Design plans of the products and description of the manufacture and remanufacturing processes, with a declaration of the suitability for reuse/remanufacturing of the carafe;
- Report that assesses the risk for the carafe due to the thermal stress and the risks derived from an incorrect use and how these could affect the reusability of the carafe.

2.8.2 Calculation of the 'Recyclability Ratio'

Concerning the recyclability of the products, the analysis regards all the material that can be potentially disassembled, separated and addressed to a recycling process.

Before the calculation it is important to estimate how the disassembly can occur. It is supposed that:

- Wires are addressed to a shredder after 4 steps of manual disassembly; Printed Circuit Board is addressed to a shredder after six steps of manual disassembly; Switches are, while wires after three 8 steps of manual disassembly. Their disassembly indices are calculated as shown in Chapter 2.5.2. Concerning the metals that they contain, the D index depends on the manual disassembly and the separation rate of the metal in the shredder. Concerning all the plastics and other materials the disassembly index is 0%. For example, the index D for the mixed (manual + mechanical) disassembly of metals results:
  - Copper in the Wires: $D = D_{manual} \cdot D_{mechanical} = 0.84 \cdot 0.85 = 71\%$ (from Table 5 $D_{manual} = 0.84$ because $n = 4$ and $t = 72$; from Table 6: 0.85 because separation of copper into shredders);
  - Copper in the Switches: $D = D_{manual} \cdot D_{mechanical} = 0.66 \cdot 0.85 = 56\%$ (from Table 5 $D_{manual} = 0.66$ because $n = 8$ and $t = 167$; from Table 6: 0.85 because separation of copper into shredders);
  - Metals in the Printed Circuit Board: $D = D_{manual} \cdot D_{mechanical}$, where D_{manual} is 0.8 (from Table 5: $n = 6$ and $t = 112$) and $D_{mechanical}$ is from Table 6: 0.95 for the iron/steel, 0.9 aluminium and 0.85 for the copper.
- Materials contained into sensor/fuses cannot be separated;
- All the other components can be separated manually. The index D is estimated on the basis of the Table 5.
- Packaging and user's manuals have a $D_{manual} = 100\%$ because they do not necessitate of disassembly;

Concerning the contamination index:

- contamination occurs for the external housing, which is painted and labelled. The contamination index is derived from Table 11 (low: C_1 = 25%; C_1' = 75%);
- the glass carafe cannot be recycled because of its borosilicate content. Therefore its Contamination index is set to: C_1 =100% and C_1' = 0%;
- contamination of hazardous substances regulated by the RoHS Directive or SVHC does not occur. The only substance potentially hazardous is the Tetrabromobisphenol-A used as flame retardant in some product's plastics (ABS). However, currently, the substance is under study and no restrictions have been introduced by the EU legislation yet[52];
- concerning the components that are addressed to shredders (Printed Circuit Board, Switches, Wires) contamination index is: C_1 = 50% and C_1' = 50%;
- no contaminants or incompatibilities among materials are detected for the other components that are manually disassembled;

Concerning the material degradation, the values of the Material Recyclability index are calculated on the basis of the Table 13.

All these values are implemented in the spreadsheet for the '*Recyclability ratio*' (Table 16).

The Recyclability Ratio of the coffee-maker results 38% in mass.

In order to allow the **verification** of the estimated values, the designer provides the following documentation:

- BOM, with the detail of material breakdown and the timing for disassembly;

2.8.3 Calculation of the 'Energy Recoverability Ratio' and of the 'Recoverability Ratio'

The calculation of the 'Energy Recoverability Ratio' is based on those materials that have an 'energy content' potentially recoverable. The calculation of the 'Recoverability Ratio' includes the burnable materials plus those materials that are recyclable.

In the present case study, energy recoverable materials include:

- the plastics contained into: the framework, the carafe handle, the pipes insulation, the switches and the Printed Circuit Board;
- the packaging;
- the user's manuals.

[52] Commission Recommendation of 30 May 2008. on risk reduction measures for the substances sodium chromate, sodium dichromate and 2,2′,6,6′- tetrabromo-4,4′-isopropylidenediphenol (tetrabromobisphenol A). 2008/454/EC.

Concerning the disassembly index of plastics, it is assumed that they have a mixed disassembly (manual + mechanical). The Disassembly index is:

- Plastics in the Printed Circuit Board: $D = D_{manual} \cdot D_{mechanical} = 0.8 \cdot 0.50 = 40\%$ (D_{manual} is 0.8 from Table 5: $n = 6$ and $t = 112$; from Table 6: 0.50 because of the separation of plastic by shredding);
- Polycarbonate in the switches: $D = D_{manual} \cdot D_{mechanical} = 0.66 \cdot 0.50 = 33\%$ (from Table 5 $D_{manual} =0.66$ because $n = 8$ and $t = 167$; from Table 6: 0.50 because separation of plastics by shredding);
- Polypropylene in the wires: $D = D_{manual} \cdot D_{mechanical} = 0.84 \cdot 0.50 = 42\%$ (from Table 5 $D_{manual} =0.84$ because $n = 4$ and $t = 72$; from Table 6: 0.50 because of the separation of plastics by shredding);

The Disassembly index of other recoverable materials is calculated analogously to the previous case of the Recyclability ratio (Chapter 2.8.2).

Contamination for the energy recovery concerns the plastics that are separated by shredding (Table 12: $C_2 = 50\%$ and $C'_2 = 50\%$). No other contaminations are detected due to the absence of hazardous substances, SVHC or other materials that could potentially contribute to the emission of hazardous substances.

The calculation data-sheet of the Recoverability ratio is then showed in Table 16.

The Energy Recoverability Ratio of the coffee-maker results 30.3% in mass.

The Recoverability Ratio of the coffee-machine results 61.6% in mass.

In order to allow the **verification** of the estimated values, the designer provides the following documentation:

- BOM, with the detail of material breakdown and the timing for disassembly;

2.8.4 Calculation of a ‘Reusability/Recyclability’ and ‘Reusability/Recoverability’ indices

The combined ‘Reusability/Recyclability’ and ‘Reusability/Recoverability’ indices have been calculated for the exemplary coffee-maker. Results are shown in Table 17. Assumptions are the same of previous Chapters 2.8.1, 2.8.2 and 2.8.3.

It results that the ‘Reusability/Recyclability’ index amounts to 43.8% and the ‘Reusability/Recoverability index’ to 63.5%.

Table 17 Example: calculation of the ‘Reusability/Recyclability ratio’ and ‘Reusability/Recoverability ratio’ of a coffee-maker

Component		Details		Reusability			Recyclability				Recoverability				Reusability-recyclability	Reusability-recoverability
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{recovery}$	$(m_{recycle} + m_{E\text{-}recovery})$	$m_{reuse/recycle}$	$m_{reuse/recovery}$
Plastic handle	1.1	Polycarbonate (PC)	0.05	100%	56%	2.8.E-02	98%	100%	77%	3.8.E-02	98%	100%	4.9.E-02	5.0E-02	5.0E-02	5.0E-02
Glass pot	1.2	Glass	0.5	100%	25%	1.3.E-01	98%	0%	75%	0.0.E+00				0.0E+00	1.3E-01	1.3E-01
		Steel	0.01	100%	100%	1.0.E-02	98%	100%	100%	9.8.E-03				9.8E-03	1.0E-02	1.0E-02
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS)	0.05				98%	100%	84%	4.1.E-02	98%	100%	4.9.E-02	5.0E-02	4.1E-02	5.0E-02
Framework /supports	3.1	Steel	0.08				84%	100%	100%	6.7.E-02				6.7E-02	6.7E-02	6.7E-02
		Steel	0.01				84%	100%	100%	8.4.E-03				8.4E-03	8.4E-03	8.4E-03
Metal heating plate	3.2.1	Copper	0.1				72%	100%	100%	7.2.E-02				7.2E-02	7.2E-02	7.2E-02
		Steel	0.04				72%	100%	100%	2.9.E-02				2.9E-02	2.9E-02	2.9E-02
Resistive heating element	3.2.2	Copper	0.06				72%	100%	100%	4.3.E-02				4.3E-02	4.3E-02	4.3E-02
Wires	4	Copper	0.075				71%	50%	100%	2.7.E-02				2.7E-02	2.7E-02	2.7E-02
		Polypropylene (PP)	0.025				0%	50%	81%	0.0.E+00	42%	50%	5.3.E-03	5.3E-03	0.0E+00	5.3E-03
Sensors/ fuses	5	Various (metals, glass)	0.02				0%	0%	0%	0.0.E+00				0.0E+00	0.0E+00	0.0E+00
Printed Circuit Board	6	Copper	0.03				68%	50%	100%	1.0.E-02				1.0E-02	1.0E-02	1.0E-02
		Steel	0.02				76%	50%	100%	7.6.E-03				7.6E-03	7.6E-03	7.6E-03
		Aluminum	0.04				72%	50%	100%	1.4.E-02				1.4E-02	1.4E-02	1.4E-02
		Glass-reinforced plastic	0.03				0%	50%	0%	0.0.E+00	40%	50%	6.0.E-03	6.0E-03	0.0E+00	6.0E-03
		Other	0.01				0%	50%	0%	0.0.E+00				0.0E+00	0.0E+00	0.0E+00
		Steel	0.01				76%	100%	100%	7.6.E-03				7.6E-03	7.6E-03	7.6E-03
Pipes	7.1	Aluminum	0.6				66%	100%	100%	4.0.E-01				4.0E-01	4.0E-01	4.0E-01
Insulations	7.2	Polypropylene (PP)	0.05				66%	100%	81%	2.7.E-02	66%	100%	3.3.E-02	5.0E-02	2.7E-02	5.0E-02
Switches	8	Copper	0.01				56%	50%	100%	2.8.E-03				2.8E-03	2.8E-03	2.8E-03
		Polycarbonate (PC)	0.04				0%	50%	77%	0.0.E+00	33%	50%	6.6.E-03	6.6E-03	0.0E+00	6.6E-03
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS)	0.3				66%	75%	84%	1.2.E-01	66%	100%	2.0.E-01	3.0E-01	1.2E-01	3.0E-01
Packaging	10	Low Density Polyethylene (PE-LD)	0.01				100%	100%	71%	7.1.E-03	100%	100%	1.0.E-02	1.0E-02	7.1E-03	1.0E-02
		Corrugated Cardboard	0.4				100%	100%	16%	6.4.E-02	100%	100%	4.0.E-01	4.0E-01	6.4E-02	4.0E-01
User's Manuals	11	Paper	0.03				100%	100%	16%	4.8.E-03	100%	100%	3.0.E-02	3.0E-02	4.8E-03	3.0E-02

$\Sigma m_{E\text{-}recovery}$	0.79
$ER_{Recovery}$	**30.3%**
Total mass "m_{tot}" [kg]	2.6
Σm_{reuse} [kg]	0.16
R_{Reuse} [%]	**6.3%**
$\Sigma m_{recycle}$ [kg]	1.00
$R_{Recycle}$ [%]	**38.5%**
$\Sigma m_{recovery}$ [kg]	1.60
$R_{Recovery}$ [%]	**61.6%**
$\Sigma m_{reuse/recycle,\ i}$ [kg]	1.14
$R_{Reuse/Recycle}$ [%]	**43.8%**
$\Sigma m_{reuse/recovery,i}$ [kg]	1.73
$R_{Reuse/Recovery}$ [%]	**66.5%**

2.9 Limits of the proposed methodology and conclusions

Chapter 2.4 has introduced a set of indices for the estimation of the *RRR* potentials. Such indices are based on the fraction in mass of reusable/recyclable/recoverable compared to the overall mass of the product. As underlined in Chapter 2.4.1 and in Deliverable 1, this approach was also shared by the ISO 22628 and, successively, by the EU Directive on the EoL of Vehicles.

This approach reveals, however, a limit: the RRR of the product is dominated by the RRR of the components with the highest mass fraction. Furthermore, the mass-based indices have no relation with the environmental burdens related to the production or recycling of a material compared to another.

It was then observed the need to go 'beyond' the current approach and to identify a way to overtake such problem. In particular it is observed the need of introducing new weighting factors (related to the life cycle of materials), which could be used to estimate the potential environmental benefits related to the Reuse/Recycle/Recovery of a product (or its components).

It could happen, in fact, that a component is not relevant in term of 'mass-fraction' but to be relevant in terms of environmental burdens. This is the case, for example, of hazardous substances that, even in very small amounts, can be very relevant for the environmental profile of the product. Similar conclusion could be done for precious metals because of their high specific environmental life-cycle impacts[53].

The progress '*beyond the current state of art*' in legislation will be the scope of the next Chapter. In particular, it aims at developing a new set of *RRR* indices based on newer insights of the scientific and technical literature, particularly focused on the life cycle thinking and assessment.

[53] On this purpose, we refer to the discussion in Chapter 5.6.

2.10 Summary

The present Chapter discusses the measurement of Reusability/Recyclability/Recoverability (*RRR*) at the Design stage of a product.

The *RRR* have been defined as 'potentials' of the product related to its attitude to be reused/recycled/recovered (definitions provided in Chapter 2.2.4). These potentials are influenced by several factors, related to the product system but also related to external factors (as the technological progress).

The Chapter firstly introduces a methodology for the measurement of the *RRR* potentials. A set of indices have been defined as *fraction (in mass) of the product that is potential reusable/recyclable/recoverable.*

The defined indices are similar to those already introduced by the current legislation for the measurement of *RRR* for vehicles (i.e. based on the approach of the ISO 22628). In the proposed methods, however, additional parameters have been added in order to increase the detail of the estimations and include a more exhaustive analysis of the product EoL. The choice of these parameters followed the finding of the survey of the scientific literature as described in the Deliverable 1.

The calculation procedure is modular: it means that the proposed indices are obtained as the product of different sub-indices. The modularity of the indices allows including or excluding some of the sub-indices without compromising the methodology itself. Furthermore, new sub-indices can be added in future, reflecting additional aspects that have not been investigated at this stage. Analogously, some indexes can be modified or removed on the basis of the expected targets of the decision-makers, effectiveness, and other considerations.

Successively, a methodology for the calculation of *RRR* has been introduced in Chapter 2.4. It is based on the compilation of the product's Bill of Materials – BOM (see also Chapter 1) and on self-assessed parameters concerning the product's 'disassemblability', material contamination and material degradation. Apposite formulas and tables have been introduced to simplify the calculation (on such purpose see Chapter 2.5 and the subsequent subchapters).

Some exemplary tables for the calculation of the disassemblability, contamination and degradation have been provided. However, these tables are only illustrative of the proposed approach and they should be further refined before to be suitable for the use into EU policies.

All the collected data are integrated with the product's BOM into apposite spreadsheets (Chapter 2.6) for the calculation of the *RRR* indices. Sufficient technical documentation has to be provided to support each estimation/assessment during the calculation.

The verification of the *RRR* indices is based on self-declarations supported by technical documentation available before the product is put into the market and provided on request (e.g. a check by the competent body). Details on the verification processes are presented in Chapter 2.4.2 and sub-chapters of paragraph 2.5.

Chapter 2.8 describes an illustrative application of the methodology to a case-study (to the coffee-machine example of Chapter 1.4).

However, in Chapter 2.9 limits of such approach have been discussed. In particular, it is observed that the RRR of the product is dominated by the RRR of the components with the highest mass fraction. This could lead to a distortion of the methodology, especially if the designers have to accomplish to minimum threshold for the RRR potentials.

The next Chapters will focus on how to overcome to such problem, by identifying some additional weighting factors that consider the life-cycle environmental profile of the different materials.

3 A method to assess priority resources

3.1 Introduction

Deliverable 1 discussed the prioritisation of critical resources according to various studies and approaches described in the scientific literature. In a particular it was analyzed an interesting ongoing EC study that indentified 15 critical materials from an initial list of 41 materials (see Table 18) [EC, 2010].

Table 18 List of materials selected for criticality assessment [EC, 2010]

Aluminium	Lithium
Antimony (*)	Magnesite
Barite	*Magnesium* (*)
Bauxite	Manganese
Bentonite	Molybdenum
Beryllium (*)	Nickel
Borates	*Niobium* (*)
Chromium	Perlite
Clays	*Platinum Group Metals (PGM)*[54] (*)
Cobalt (*)	*Rare earths*[55] (*)
Copper	Rhenium
Diatomite	Silica sand/Glass sand
Feldspar	Silver
Fluorspar (*)	Talc
Gallium (*)	*Tantalum* (*)
Germanium (*)	Tellurium
Graphite (*)	Titanium
Gypsum	Tungsten (*)
Indium (*)	Vanadium
Iron	Zinc
Limestone	
(*) *Material identified as critical*	

The criteria for the selection included:

- *Economic importance*. This reflects the role that each material has into the economic sectors, taking into account the end uses of a raw material and the value of the sectors into which they flow.

[54] Platinum Group Metals (PGMs) comprise: platinum, palladium, iridium, rhodium, ruthenium and osmium
[55] Rare earths comprise: yttrium, lanthanium and the so-called lanthanides (cerium, praseodynium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, rebium, thulium, ytterbium and lutetium).

- *Supply risk*. It takes into account the political-economic stability of the producing countries, the level of concentration of the production, the potential for substitution and the recycling rate;
- *Environmental risk*. It considers the risks that that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so, endanger the supply of raw materials to the EU.

The last criterion involved the 'environmental' theme, but only in relation to possible supply risks that could arise from environmental measures of the extracting countries. However the study recognised the importance of the potential application of a life-cycle approach: it is "*recommended that further work should be developed with the aim to overcome the current data constraints*" [EC, 2010].

The present Chapter will discuss how life-cycle data of the materials could be potentially introduced into the prioritisation of the resources, and how the results could be put in relation with the previous methodology on the *RRR*.

3.2 Priority resources and life-cycle data

The scientific community is currently working on the methodologies for the prioritization of resources. Deliverable 1 has discussed some ongoing studies that analyzed various prioritisation criteria including supply risks, economic relevance and environmental risks.

It is still ongoing the debate about the prioritisation of resources based on the environmental impacts related to their extraction and treatment. It is important to underline that a *material could have very high specific environmental impacts but, at the same time, to be necessary for some specific technologies that allow great environmental benefits*[56].

These concepts have been already included in some legislation. For example the RoHS Directive restricted the use of some hazardous substances due to their potential impacts. On the other side, the RoHS has foreseen several exemptions to these restrictions, allowing the use of some hazardous for some specific uses.

According to the scopes of the project, the attention is therefore focused on the *RRR* and the potential benefits related to the reuse/recycling/recovery of the materials as a key issue for their prioritisation. In fact, improving the reuse/recycling/recovery of critical resources, ones can contribute to mitigate the supply risks of priority materials and to mitigate the environmental impacts related to the material's production, use and disposal.

The reuse implies that the product (or some components) is re-used for the scope they were produced. Products/components specifically designed for re-manufacturing are collected after their use and re-inserted into the manufacturing process of new products, after only minor

[56] For example, the use of platinum into catalytic converters for vehicles.

treatments. The full or partial reuse of a product avoids therefore the new manufacturing, with relevant environmental benefits.

The recycling is the reprocessing in a production process of the waste materials for the original purpose or for other purposes. Benefits related to recycling occur when the production of secondary materials from waste treatment has minor life-cycle impacts compared to the primary production.

The energy recovery of materials is related to their use, at the EoL of the product, as energy sources. Materials can be directly incinerated with energy recovery, or converted into other energy carriers (e.g. by gasification, pyrolysis, biodegradation). The benefits of the energy recovery are therefore related to the avoided use of conventional energy carriers.

The following chapters will focus on the life-cycle impacts related to the production of primary and secondary materials. Successively, Chapter 3.4 will focus on the calculation of benefits related to the reuse/recycle/recovery and their implementation into the methodology for the measurement of *RRR*.

3.2.1 Life-cycle data of the production of primary and secondary materials

The production of primary materials causes environmental impacts due to the extraction of the resources, their transport and transformation, up to the production of the material. The LCA methodology can be used to account the impacts that arise during all these life-cycle stages[57] [ISO, 14040].

For those materials that are currently technologically recyclable*, it is also possible to calculate the life-cycle impacts due to the production of a unit of 'recycled' material.*

The comparison of life-cycle data related to the production of primary and secondary materials is useful to assess the potential benefits related to the recycling.

On such purpose it is possible to define the <u>*differential impact* δ,</u> *meaning the difference among the impact to produce one unit of primary material and that to produce the same quantity from recycled scraps. As bigger is such differential, as higher is the potential environmental 'benefit' related to the recycling*. In formula:

$$\textbf{\textit{Formula 17}} \quad \delta_{n,I} = I_{n,primary} - I_{n,recycled}$$

Where:

- 'δ' = differential impact of the generic 'n^{th}' material and concerning the generic I^{th} impact category/index;

[57] The accounting of the environmental impacts from the extraction of the resources to the production of the material is generally named 'cradle-to-gate' approach.

- '*primary'* = impact referred to the production process of one unit of primary material;
- '*recycled* = impact referred to the production of one unit of recycled material.

It is also interesting to calculate the *percentage differential impact* Δ [%]*, intended as the ratio among the differential impact and the impact to produce one unit of primary material*. In formula:

$$\textbf{\textit{Formula 18}} \quad \Delta_{n,I} = \frac{I_{n,primary} - I_{n,recycled}}{I_{n,primary}} \cdot 100$$

For example, assuming as '*n*' the copper and as 'I' the emission of CO_2, the *formulas 17 and 18* become:

$$\textbf{\textit{Formula 19}} \quad \delta_{Copper,CO_2} = CO_{2,Copper,vigin} - CO_{2,Copper,recycled}$$

$$\textbf{\textit{Formula 20}} \quad \Delta_{Copper,CO_2} = \frac{CO_{2,Copper,vigin} - CO_{2,Copper,recycled}}{CO_{2,Copper,vigin}} \cdot 100$$

Note that the differential impact **δ** can have negative values and positive values up to infinite. In particular, negative values can occur when the recycling process causes higher impacts than the manufacturing of the virgin one.

Therefore, the differential impact **δ** and the percentage differential impact Δ can be considered as a measure of the potential 'environmental benefits' achievable by the materials recycling. High values of the differential impacts identify 'critical' or 'priority' materials for recycling on which focus the attention of designers and decision makers.

The following chapter 3.3 will perform a survey in the scientific literature of LCA data about primary and secondary production of some exemplary materials and the calculation of the differential impact δ.

3.3 Prioritization of the resources: an exemplary application

The methodology for the resource prioritisation proposed in previous chapters can be applied referring to any life cycle impact category. The following chapters present an exemplary application of the methodology to two impact categories:

- the Primary Energy Consumption (PEC) : this is an indicator representing the cumulative consumption of primary energy for the entire process chain of the material/product.
- the Global Warming Potential (GWP): is an index that has been introduced to assess the contribution of a greenhouse gas to the global warming. Characterization factors for greenhouse gases are calculated and updated by the Intergovernmental Panel on Climate Change [IPCC, 2007].

In order to apply formulas 17 and 18, we performed a survey about available LCA data about the production of primary and secondary/recycled materials. The results of the survey are described in the following sections.

3.3.1 Survey of LCA data

The survey concerned the materials listed in Table 18 and some additional recyclable materials that are commonly used for the production and packaging of electric and electronic products including: glass, brass, cadmium, lead, paper/cardboard and main thermoplastics. Results are summarized in Annex 2.

First of all the survey focused on the European Reference Life Cycle Database (ELCD) database [ELCD, 2010]. The available data inventories concerned zinc, gypsum, crushed stone and the thermoplastics. Available data about metals (as steel, stainless steel, aluminium copper and lead) were not included because referred to average production mix and, therefore, already including input/output flows from both primary and secondary production.

Successively the survey focused on other environmental life-cycle database including GaBi [GaBi 4] and BUWAL [BUWAL, 1996]. Finally the analysis was extended to other scientific sources, including data from producers associations (as the European Aluminium Association, the Nickel Institute and Plastic Europe) and data published into scientific journals and proceedings. The use of heterogeneous data sources is however affected by several limits. These have been discussed in Chapter 3.3.3.

Note that the life cycle inventory data are used only to illustrate the discussed methodology. Therefore, the use of data in this study does not reflect any endorsement of the data, nor the associated databases.

Table A2.1 (Annex 2) presents the PEC and GWP related to the primary and secondary productions and the related bibliographic references. Various references have been identified, showing also very different values. Differences can be ascribed to various reasons as for example:

- concentration of the ores in the mining;
- typology of technology adopted for the production/recycling;
- typologies of energy sources that are used for the processing (and in particular energy mix for the production of the electricity);
- location of the mining and impacts related to transportation;
- concentration and contamination of the recycled materials into the collected scraps.

LCA data have been re-arranged in a new Table A2.2, considering an average value from the different detected references. Concerning some materials (as aluminium and zinc) data were referred to only one reference because supposed more representative. More details are provided in Table A2.2.

However, concerning the majority of the materials LCA data were incomplete or missing. In particular Table A2.3 shows materials for which LCA data were missing (concerning the primary or the secondary production or both).

The data shortage is related to several reasons, as:

- the exploitation of some materials is relatively recent. Therefore the scientific community had not the opportunity to collect information and to carry out LCAs;
- some applications of resources are so new that relevant mass flows of post-consumer materials will reach the waste management sector only in few years;
- concerning some materials, until today, the recycling technologies are not available at commercial scales (or there are only some initial attempts in small pilot plants);
- some critical resources are mostly mined into political unstable countries. Such situation obstruct the acquisition of environmental information about extraction and production processes;
- some materials are also characterized by a very restricted marked controlled by few producing companies that refused to spread information about their production process considering them as proprietary information.

Furthermore, several materials (as molybdenum, chromium, manganese, niobium, and beryllium) are mostly used as alloying elements for the production of other metals (as steel, stainless steel, copper or aluminium). Therefore, these materials are only indirectly recycled by the recycling of steel, stainless steel and copper.

Available values have been plotted in the following graphics. It is possible to note a very good correlation among PEC and GWP values for the material processing (Figure 11), confirming that emissions of greenhouse gases are strictly related to the energy consumption, and in particular, to the consumption of fossil fuels.

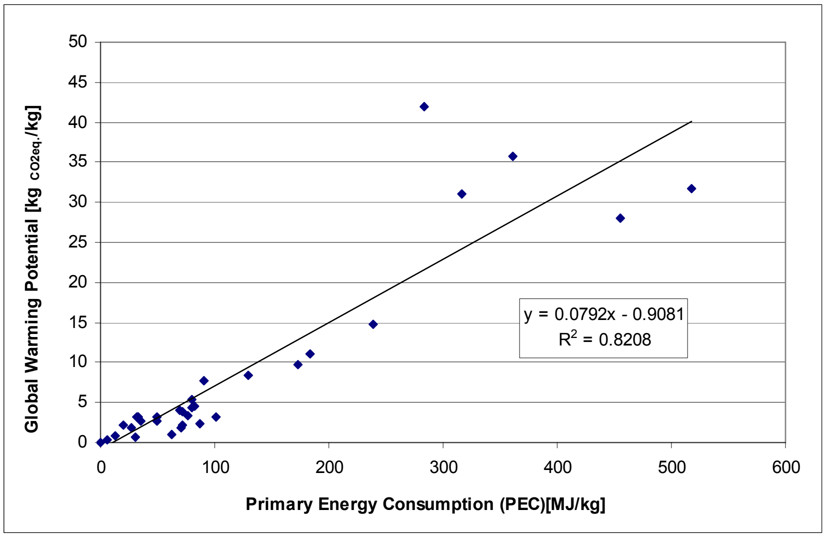

Figure 11 Primary Energy consumption (PEC) vs. Global Warming Potential (GWP) for the primary production of various materials, and trend-line[58].

Figure 12, instead shows a very poor correlation among the energy expenditure for the production of primary or secondary materials. In fact, the PEC for the primary production is generally related to the material concentration in the ores or to the typology of used energy sources; secondary production is instead related to other factors (as the scrap collection and collection or the used technology for the recycling). Furthermore recycling of metals is generally less energy consuming that recycling of plastics.

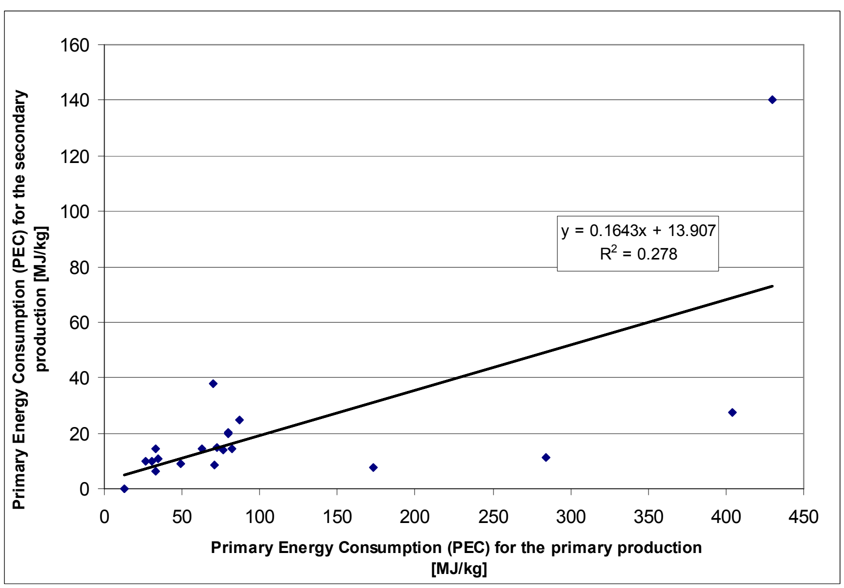

Figure 12 Primary Energy consumption (PEC) for primary vs. secondary production of various materials, and trend-line[59]

[58] Figure 10 has been obtained from the values of PEC and GWP of primary production of materials (Tables A2.1 and A2.3), excluding the values of Rare Earths (because specifically referred to the Chinese production context).

3.3.2 Calculation of the *differential impacts indices* 'δ' and 'Δ'

According to the formulas 23 and 24 and the data of Table A2.1, some exemplary differential impact indices δ and Δ have been calculated. Results are summarized in Table 19.

Materials have been listed for decreasing values of Δ. It is possible to observe that majority of metals have generally higher values (from 96% to 80%) of the differential indices Δ_{PE} and Δ_{GWP}. Other metals have lower values but still close to 60%. Lower values are related to materials processed by scraps with high contamination levels.

Plastics have variable data: some plastics (as PE-HD, PS and PET) have values of the differential indices higher than 80%, comparable to metals; other plastics (as PP) have lower values, related mostly to the performance of recycling technology. We underline that the differential index does not take into account the loss of quality of materials due to the recycling process (as instead done for the measurement of the material recyclability).

At the bottom of the Table 19 there are grouped materials whose recycling produces less relative advantage in term of saved energy or greenhouse emissions. However it does not imply that their recycling is not preferable. In fact some of them (as steel, stainless steel and cardboard) are some of the most spread and recycled materials.

Table 19 Differential impacts indices 'δ' and 'Δ' ***calculated for various materials***

	Primary production		**Secondary production**		δ_{PEC}	Δ_{PEC}	δ_{GWP}	Δ_{GWP}
	[MJ/kg]	[$kg_{CO2eq.}$/kg]	[MJ/kg]	[$kg_{CO2eq.}$/kg]	[MJ/kg]	[%]	[$kg_{CO2eq.}$/kg]	[%]
Magnesium	284.0	42.0	11.40	1.7	272.60	*96.0%*	40.30	*96.0%*
Aluminum	173.09	9.67	7.68	0.5	165.40	*95.6%*	9.17	*94.8%*
Nickel	404.0	24.80	27.70	n.a.	376.30	*93.1%*	-	-
PE-HD	70.84	1.92	8.65	0.6	62.19	*87.8%*	1.31	*68.0%*
PS	82.04	4.49	14.45	1.0	67.59	*82.4%*	3.54	*78.7%*
Zinc	49.28	3.17	9.0	0.5	40.28	*81.7%*	2.69	*84.9%*
PET	76.49	3.40	14.08	1.0	62.41	*81.6%*	2.44	*71.8%*
Copper	33.0	3.20	6.30	0.4	26.70	*80.9%*	2.76	*86.3%*
Platinum	218,500	n.a.	43,700	n.a.	174,800	*80.0%*	-	-
PE-LD	72.17	2.10	15.0	0.9	57.17	*79.2%*	1.20	*57.3%*
Paper	62.76	0.97	14.27	0.5	48.49	*77.3%*	0.46	*46.9%*
Brass	80.0	4.39	20.0	1.1	60.0	*75.0%*	3.29	*74.9%*
Stainless steel	80.0	5.32	20.50	1.6	59.50	*74.4%*	3.72	*69.9%*
PP	86.64	2.33	24.90	1.1	61.74	*71.3%*	1.22	*52.4%*
Steel	34.25	2.98	11.0	0.8	23.25	*67.9%*	2.16	*72.4%*
Titanium	430.0	n.a.	140.0	n.a.	290.0	*67.4%*	-	-
Cardboard	30.38	0.68	10.09	0.6	20.29	*66.8%*	0.12	*17.5%*
Lead	26.94	1.78	10.0	0.5	16.94	*62.9%*	1.25	*70.2%*
Tin	33.30	3.20	14.20	1.3	19.10	*57.4%*	1.90	*59.4%*
Cadmium	70.0	n.a.	38.0	n.a.	32.0	*45.7%*	-	-
Glass	12.68	0.77	n.a.	0.53	-	-	0.24	*31.1%*

n.a. Data not available

[59] Figure 11 has been obtained from the values of PE of primary and secondary production of materials (Tables A2.2).

The values of indices Δ_{PEC} and Δ_{GWP} are quite similar, due to the strict correlation among these two impacts categories. These figures should be considered as only illustrative of the methodology. A more detailed analysis should consider different and more comprehensive impact categories. Note that the prioritization based on other environmental impacts categories could lead to very different results.

Higher values of δ *and* Δ identify the materials that grant higher environmental benefits when recycled. Efforts of designers and decision maker should be addressed to avoid that those materials would be placed into landfill, promoting instead their separation from the waste flow and their recycling.

On such purpose, design requirements could be introduced to facilitate the reuse/recycle of identified priority materials, including for example:

- the content of priority materials has to be detailed into the BOM;
- the access and separation of priority materials has to be facilitated, in order to simplify their disassembly at the EoL;
- the contamination of priority materials with other components (e.g. inks, labels, other incompatible materials) has to be avoided, unless demonstrated that this choice cannot be avoided.

On the other side, low values of δ *and* Δ identify materials whose recycling has lower benefits. This can be related to intrinsic properties of the material, to the available technologies for the recycling and also to the “quality” of secondary scraps (high contaminated scraps, in fact, need more energy intensive processing). Materials with low values of the indices δ *and* Δ have to be studied in order to identify the reasons for the high environmental impacts for their recycling and in order to assess if there are margins for their reduction.

3.3.3 Limits of the results

The proposed methodology for the resource prioritisation can be potentially applied referring to any life cycle impact category. The methodology has been illustrated only on two selected impact categories. It is important to remind that the selection different reference impact categories could leas to very different results;

It is underlined that the reliability of the analysis is strictly related to the reliability of the environmental data. The previous survey identified some limits concerning the available data:

- The investigated data have been often published with little additional information (metadata) concerning the system boundaries and all the other key issues of the LCA. It is therefore very difficult to check the data quality and the assumptions under which data have been calculated;

- Data about the production and/or the recycling of some materials are missing. As previously observed, the exploitation of some materials (as rare earth) grew up only in the last decade and LCA studies concerning their primary or secondary production are generally missing;
- In many published paper and report data are often not transparently presented. Often data are also presented as aggregated. Therefore, needed data have to be extrapolated from available information;
- Few data about the recycling processes of the studied materials have been available;
- The investigated dataset were often not up-to-date.

In order to improve the quality of results, possible suggestions are:

- Consistency among used LCA data should be granted. The ELCD database grants that all the data set are consistent. Consistency could be granted, for example, by using study that are compliant with the ILCD Handbook [ILCD, 2010] and available via the ILCD Data Network;
- Data should be representative of the European production context. When different production technologies are suitable, data should refer to the technology mix adopted in the EU.

3.4 Resource prioritization and Reusability, Recyclability and Recoverability

The previous chapters discussed the prioritisation of the resources based on a life-cycle data. This represents a methodology to assess the potential environmental advantages related to the recycle of materials. Similarly, it is also possible to prioritize the materials based to the potential benefits achievable by reuse of recovery, developing indices similar to the 'differential impact δ'. Such indices could also represent a way to prioritise choices about the product EoL, in line also with the legislative priorities.

Figure 13 shows the waste hierarchy as introduced by the European Legislation [EU, 2008]. It is observed that:

- The Energy Recovery[60] of materials partially allows the recovery of the energy embodied by the material. This energy can be 'extracted' by some specific treatments e.g.: incineration, anaerobic digestion, gasification, and pyrolysis. Note that after the treatment, the material is structurally 'dissipated' and, therefore, this option excludes a further potential recovery.
- The Recycle involves those materials that are potentially recyclable. These can be used as secondary materials for a new manufacturing, replacing (fully or in part) primary materials. Materials can be recycled several times, compatibly with their physical/chemical structure. After recycling, combustible materials can still be addressed to the energy recovery.
- The Reuse implies that a product is fully or partially used for the same purpose for which it was conceived. Unless minor processing (e.g. checking, cleaning, partial repairing/refurbishing), the reuse implies that reused components have not to be manufactured again. Reuse can occur compatibly with the physical/chemical properties of the materials. Reused materials can be successively addressed to recycling or/and to the energy recovery.

The following paragraph will introduce first a methodology for the calculation of the benefits related to Reuse/Recycle/Recovery. The result will be successively implemented to the indices previously defined in Chapter 2, defining a new methodology for the measurement of the *RRR* potentials

[60] On the basis of the EU waste legislation, the recovery process includes both the energy recovery and the recycling. In the present chapter only the energy recovery is considered, in order to clearly distinguish it from the recycling.

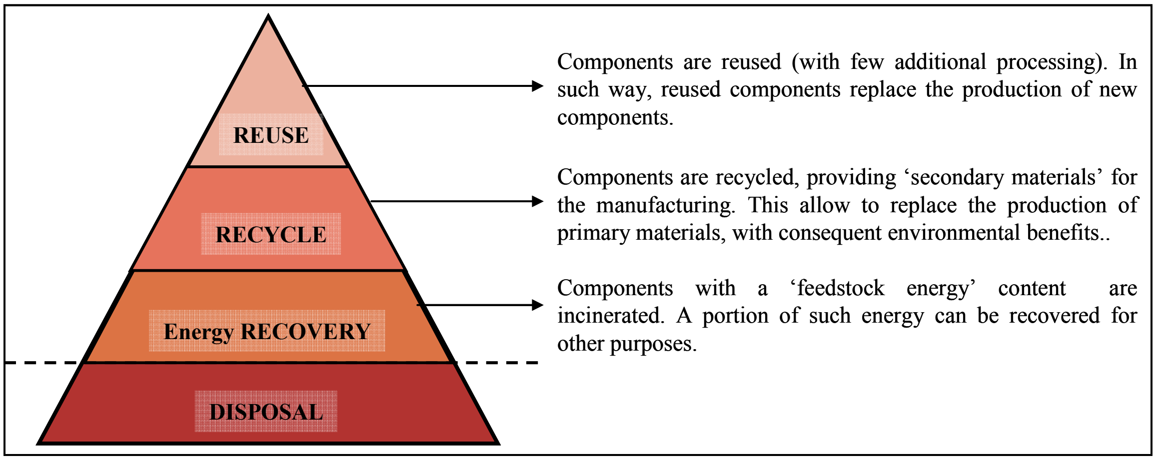

Figure 13 Waste Hierarchy and related environmental benefits

3.4.1 Energy Recovery of materials: related environmental benefits

Deliverable 1 discussed the Recovery of waste as introduced by the European legislation[61]. In particular, alternatives for the energy recovery of waste have been discussed. The following chapters will illustrate the potential energy/environmental benefits associated to these various alternatives.

3.4.1.1 Energy Recovery by incineration

The recovery by incineration represents the most common energy recovery treatment. The energy potential recoverable from a product can be estimated as:

$$\textbf{\textit{Formula 21}} \quad \mathrm{ER}_{Potential} = \sum_i \sum_k m_{k,i} \cdot HV_{k,i}$$

Where:

- $\mathrm{ER}_{\mathrm{Potential}}$ = Energy potential recoverable by incineration from a product [MJ];
- '$m_{k,i}$' = mass of the k^{th} material of the i^{th} component potentially recoverable [kg]; '
- '$\mathrm{HV}_{k,i}$' = (higher or lower) Heating Value of the material $m_{k,i}$ [MJ/kg];

The energy potentially recoverable by incineration can be therefore estimated on the basis of the product's BOM, the mass of combustible materials and their related heating values.

The potential environmental benefits related to the energy recovery of products can be estimated supposing that the electricity produced will substitute electricity produced by conventional plants. In formula, it results:

[61] Deliverable 1 – Chapter 2.5.

$$\textbf{\textit{Formula 22}} \quad \mathrm{ER}_{\mathrm{Benefits}} = \eta \cdot \frac{\mathrm{ER}_{\mathrm{Potential}}}{3.6} \cdot I$$

Where:

- $ER_{Benefit}$ = Potential environmental benefit related to the energy recovery of the product [unit[62]]
- $ER_{Potential}$ = Energy potential recoverable from a product (formula 21) [MJ];
- 'I' = generic impact related to the production of 1 kWh of electricity[63] [unit/kWh];
- 3.6 = Conversion factor from MJ to kWh;
- η = energy conversion factor.

The factor 'η' depends on the characteristics of the incineration plants. The energy recovered from combustible materials is recovered as heat; this can be transferred to a 'medium' (e.g. a heat transfer fluid) and successively transformed to e.g. mechanical energy or electricity. During each transformation, energy losses occur. The factor 'η' synthesizes the efficiency of the full process and can be considered as the percentage of the overall potential energy that can be usefully exploited. For example, if the heat of incineration is used to produce electricity, η commonly varies between 0.2 - 0.3. Higher values of η can be obtained if also heat is recovered and distributed to final users.

Note that Formula 22 is only illustrative. The coefficient there implemented are, in fact, strongly related to the assumptions of the calculation (i.e. recovery by incineration and use of the recovered energy for the production of electricity). Actually, depending on the considered technology for the energy recovery, a further fraction of the energy embodied into materials could be recovered (e.g. recovery of the heat and distribution to users) with higher overall benefits. On such purpose, an 'average European' technology for the incineration could be selected, adopting some average values of efficiency of the energy conversion. However, the new assumptions would not modify the structure of Formula 22.

Analogously, the adoption of different recovery alternatives changes the estimated environmental benefits. These will be discussed in the following paragraphs.

3.4.1.2 Energy Recovery by anaerobic digestion

Another alternative of energy recovery is the anaerobic digestion of biodegradable waste to produce biogas. This is assumed a substitute of the natural gas for energy uses[64].

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[62] The unit of measure [unit] depends on the considered environmental impact category. For example kilograms of avoided greenhouse gases expressed as [kg_{CO2eq}.].

[63] For the calculation in the present deliverable, we refer to the inventory of "EU-27 Electricity Mix AC; consumption mix, at consumer; < 1kV" of the European Reference Life Cycle Database (ELCD) [ELCD, 2010].

[64] Note that biogas needs to be purified before being used in normal combustion plant, because it contains corrosive substances as H_2S.

$$\textbf{\textit{Formula 23}} \quad \mathrm{ER}_{A-Digestion} = \sum_i \sum_k m_{k,i} \cdot \phi_{k,i} \cdot HV_{Biogas_{k,i}}$$

Where:

- $ER_{A\text{-}Digestion}$ = Energy potential recoverable by anaerobic digestion of a product [MJ];
- '$m_{k,i}$' = mass of the k^{th} material of the i^{th} component potentially recoverable [kg];
- $\phi_{k,i}$ = specific production of biogas in the digester per unit of decomposed biodegradable material $m_{k,i}$ [kg_{Biogas}/kg];
- '$HV_{Biogas\text{-}k,i}$' = (higher or lower) Heating Value of the biogas produced from the decomposition of the material $m_{k,i}$ [MJ/kg_{Biogas}];

Note that the parameter 'ϕ' largely depends on the biodegradability of the material and the digester's characteristic. Even the HV_{Biogas} is variable and it depends on the composition of the biogas and, mainly, on the concentration of methane.

The Deliverable 1 – Chapter 2.5 – presented some reference value of production of biogas from the degradation of some materials. For example, the decomposition of an average paper/cardboard batch can produce on average 0.143 m^3 of methane per kg of treated dry matter [Pommier et al., 2010]. Assuming to use the gas into a combustion plant, and assuming an average calorific value of methane (35.8 MJ/ m^3) it results that the potential energy recoverable amounts to about 5 MJ per kg of paper/cardboard[65].

Successively, the environmental benefits related to the anaerobic digestion can be estimated similarly to Formula 22.

3.4.1.3 Energy Recovery by pyrolysis/gasification

Other alternative energy recovery options of waste include pyrolysis and gasification (Deliverable 1 – Chapter 2.5.2). These treatments are based on the heating of waste into special plan in absence/restriction of oxygen. The main outputs of the process are:

- 'syngas' that can be use as input for various processes (e.g. as fuel for combustion plan or, when liquefied, as input for the synthesis of plastics) and,
- in some case, a solid residual similar to coal (char).

Assuming that the main output of the pyrolysis/gasification would be the syngas[66] used as fuel, the energy potential recoverable by pyrolysis/gasification can be estimated as:

$$\textbf{\textit{Formula 24}} \quad \mathrm{ER}_{Pyr./Gas.} = \sum_i \sum_k m_{k,i} \cdot \varepsilon_{k,i} \cdot HV_{Syngas_{k,i}}$$

Where:

[65] Note that this energy output does not include the energy required to digest the biodegradable substance. From a life-cycle perspective, impacts to the digestion should also be included in the energy/environmental balance.
[66] Note that the pyrolysis and gasification processes are generally set to maximize the syngas output.

- '$m_{k,i}$' = mass of the k^{th} material of the i^{th} component potentially recoverable [kg];
- $\varepsilon_{k,i}$ = specific production of syngas in the pyrolysis/gasification plant, per unit of treated material $m_{k,i}$ [kg_{Syngas}/kg];
- '$HV_{Syngas-k,i}$' = (higher or lower) Heating Value of the syngas produced by pyrolysis/gasification of the material $m_{k,i}$ [MJ/kg_{Syngas}];

Analogously to incineration and bio-degradation, the parameter 'ε' largely depends on the typology of the material and the plant's characteristic. Even the HV_{Syngas} is variable and it depends on the composition of the gas and, mainly, on the concentration of methane and carbon dioxide.

For example, the pyrolysis/gasification of 1 kg of average plastic batch can produce [Jung and Fontana, 2007]:

- By Pyrolysis: ε = 0.89 kg_{syngas}/kg; (HV_{syngas} = 32 MJ/kg),
- By Gasification: ε =1.02 kg_{syngas}/kg (HV_{syngas} =31.9 MJ/kg).

Even in this case, the environmental benefits related to the pyrolysis/gasification can be estimated similarly to Formula 22.

If the liquefied syngas is used to produce plastics, the environmental benefits would be estimated in terms of conventional fuel (e.g. oil) substituted.

3.4.2 Recycling of the materials and related environmental benefits

As observed in Deliverable 1, the recycling is often hampered more by economic problems than by the technological feasibility. Especially concerning metals, the recycling if theoretically almost always possible, but sometimes other difficulties arise (e.g. the material contamination by tramp substances or the lack of technologies to separate the substances). In some cases, the absence of suitable recycling facilities for some materials is due to the very fast development of their use in the last decade[67] .

The recycling of materials can produce relevant benefits. The differential impacts of Table 19 shows the energy saving (or the avoided emissions of greenhouse gases) that can be achieved by recycling some exemplary materials.

For example, considering the differential index 'δ_{GWP}' of aluminium from Table 19, it results that the recycling of 1 kg aluminium allows the saving of 9.2 kg CO_{2eq}.

Analogously, it is possible to estimate the overall potential environmental benefits related to the recycling of the materials constituting a product, as:

$$\textbf{\textit{Formula 25}} \quad \text{Recycle}_{Benefit} = \sum_i \sum_k m_{i,k} \cdot \delta_{i,k,I}$$

[67] For example the tantalum that was almost unused one decade ago and, nowadays, is instead largely contained in mobiles and notebooks.

Where:

- $Recycle_{Benefit}$ = Environmental benefits that are potential achievable by recycling the materials of a product [unit];
- '$m_{k,i}$' = mass of the k^{th} material of the i^{th} component potentially recyclable [kg];
- '$\delta_{i,ki,I}$' = differential impact index related to the k^{th} material of the i^{th} and the I^{th} impact category (as in formula 17) [unit/kg].

To estimate the environmental benefits related to the recycling it is therefore necessary to have the BOM of the products and the differential impact indices related to each product's materials.

For example, '$m_{i,k}$' could be the mass (*0.1 kg)* of the copper metal heating plate of the example in Figure 10; considering as impact category 'I' the GWP, it results '$\delta_{copper,GWP}$'= 2.76 kg CO_2eq (from Table 19).

3.4.3 Reuse of the materials and related environmental benefits

The reuse implies that the product (or some components) is re-used for the scope they were produced, after only minor treatments (e.g. quality checking, cleaning, repairing, etc.) that do not change the function of the product.

Following a substitution approach, we could assume that the reuse of an old component would substitute the manufacturing of a new one. The full or partial reuse of a product avoids therefore the new manufacturing, with relevant environmental benefits.

These benefits are higher than those related to the recycling. In fact, in the recycling processes the scraps are however addressed to a recycling treatment, causing some environmental impacts. The environmental benefits of recycling are, therefore, related to the differences occurring among the impacts new manufacturing process and the impacts of the recycling process.

The environmental benefits of the full (or partial) reuse of a product amount to the impacts that the manufacturing would cause if only primary materials are used. In formula it results:

$$\textbf{\textit{Formula 26}} \quad \text{Reuse}_{Benefits} = \sum_i \sum_k m_{i,k} \cdot I_{i,k}$$

Where:

- $Reuse_{Benefit}$ = Environmental benefit related to the reuse of a product [unit];
- $m_{i,k}$' = mass of the k^{th} material of the i^{th} component potentially reusable [kg];
- $I_{i,k}$ = Impact related to the 'primary' production of the k^{th} material of the i^{th} component that is potentially reusable [unit/kg];

For example, '$m_{i,k}$' could be the mass (*0.5 kg)* of the glass pot of the example in Figure 10; considering as impact category 'I' the GWP, it results: '$I_{Primary,glass}$'= 0.77 kg $CO2_{eq}$ (from Table 19).

Actually, Formula 26 approximates the environmental benefits related to the reuse, because:

- The impact related to the production of a product includes the impact related to the manufacturing of the raw material plus the impact related to the other stages (e.g. the manufacturing, transportations, the assembly, etc.). Consequently, Formula 26 underestimates the potential benefits related to the reuse;
- The reuse implies anyway some environmental impacts related to processing, including the impacts due to the transportation of the reusable components, the cleaning and checking of the product, and all the further processing (e.g. repairing, polishing, re-painting, etc.). Such impacts should be deducted from the calculated benefits. Consequently, Formula 26 overestimates the potential benefits related to the reuse.

A more precise computing of the environmental benefits would require a more detailed LCA of the considered product and its reuse process. Results of Formula 26 are useful to estimate the order of magnitude of the potential benefits related to the reuse.

3.5 Integration of resource prioritisation and environmental benefits with indices for the measurement of RRR

The previous paragraphs discussed the potential benefits related to the reuse, the recycle and the energy recovery of products. The next step of the analysis concerns the application of the above mentioned formulas to the methodologies for the measurement of the Reusability/Recyclability/Recoverability potentials (Chapter 2.5).

The scope is to produce a new set of indices that could enclose information about the potential benefits related to reuse/recycle/recovery with the indices concerning the product's 'disassemblability', material contamination and material degradation.

These indices can be a support for the Ecodesign of the products. Designers could, for example, focus their attention on components that have the largest potential benefits, in order to improve, for example, the disassemblability, of the component or to avoid contamination among different materials.

The following formulas will be referred to a generic impact category 'I' for the resource prioritisation. However, the illustrative applications of the formulas will refer to the prioritisation of resources shown in Table 19, based on the GWP.

3.5.1 The Reusability Benefit Ratio

Formula 2 introduced the 'Reusability Ratio' ($R_{Recycle}$) expressed fraction in mass of the product that is potentially reusable. This formula can be modified by introducing the **Reusability Benefit Ratio ($R_{eusability,Benefit}$)** [%]:

'**Reusability Benefit Ratio**' (**$R_{eusability,Benefit}$**) [%]: it is the ratio between the environmental benefits related to the potential reuse of the product (of its parts), with the maximum benefits that is potentially achievable by the full product reuse. It is calculated as:

Formula 27 $$Reusabiliy_{Benefit} = \frac{\mathrm{Reuse}_{\mathrm{Benefit}}}{\mathrm{Reuse}_{\mathrm{Benefit,Max}}} \cdot 100$$

Where:

$$\mathrm{Reuse}_{\mathrm{Benefit}} = \sum_i \sum_i D_{i,k} \cdot M_{Di,k} \cdot m_{i,k} \cdot I_{\mathrm{i,k}}$$

$$\mathrm{Reuse}_{\mathrm{Benefit,Max}} = \sum_i \sum_i m_{i,k} \cdot I_{\mathrm{i,k}}$$

- $\mathrm{Reuse}_{\mathrm{Benefit}}$ = Environmental benefit related to the potential reuse of the product [unit];
- $\mathrm{Reuse}_{\mathrm{Benefit,Max}}$ = Maximum potential environmental benefit related to the reuse of the product [unit];
- All the used symbols are those already introduced in Chapter 2.5 and Chapter 3.4.3.

The formula is implemented in the calculation spreadsheet of Table 20.

Table 20 Spreadsheet for the calculation of the Reusability Benefit Ratio

Component		**Details**		Disassemblability	Material Degradation	Impact for primary production	Potential benefits related to reuse
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	M_D [%]	I_{GWP} [kg_{CO2eq}/kg]	[kg_{CO2eq}]
				$\mathrm{Reuse}_{\mathrm{Benefit}}$ [kg_{CO2eq}]			
				$\mathrm{Reuse}_{\mathrm{Benefit,Max}}$ [kg_{CO2eq}]			
				Reusability Benefit Ratio "$\mathrm{Reusability}_{\mathrm{Benefit}}$" [%]			

3.5.2 The Recyclability Benefit Ratio

Formula 2 introduced the 'Recyclability Ratio' ($R_{Recycle}$) expressed fraction in mass of the product that is potentially recyclable. This formula can be modified by introducing the **Recyclability Benefit Ratio (*R*$_{ecyclability,Benefit}$)** [%]:

'**Recyclability Benefit Ratio**' (***R***$_{ecyclability,Benefit}$) [%]: it is the ratio between the environmental benefits related to the potential recycling of the product (or its parts), with the maximum benefits that is potentially achievable by recycling. It is calculated as:

Formula 28 $$Recyclability_{Benefit} = \frac{\text{Recycle}_{\text{Benefit}}}{\text{Recycle}_{\text{Benefit,Max}}} \cdot 100$$

Where:

$$\text{Recycle}_{\text{Benefit}} = \sum_i \sum_k D_{i,k} \cdot C_{1_{i,k}} \cdot M_{Ri,k} \cdot m_{i,k} \cdot \delta_{\text{i,k,I}}$$

$$\text{Recycle}_{\text{Benefits, Max}} = \sum_i \sum_k m_{i,k} \cdot \delta_{\text{i,k,I}}$$

- $\text{Recycle}_{\text{Benefit}}$ = Environmental benefit related to the potential recycling of the product [unit];
- $\text{Recycle}_{\text{Benefits, Max}}$ = is the 'maximum' potential benefits related to the recycling of the product;
- All the used symbols are those already introduced in Chapter 2.5 and Chapter 3.4.2.

The formula is implemented in the calculation spreadsheet of Table 21.

Table 21 Spreadsheet for the calculation of the Recyclability Benefit Ratio

Component		**Details**		Disassemblability	Contamination Index	Material Degradation	Differential impact	Potential benefits related to recycling
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	C'_1 [%]	M_R [%]	δ_{GWP} [$kg_{CO2eq.}$/kg]	[$kg_{CO2eq.}$]
				$\text{Recycle}_{\text{Benefit}}$ [$kg_{CO2eq.}$]				
				$\text{Reclycle}_{\text{Benetit,Max}}$ [$kg_{CO2eq.}$]				
				Recyclability Benefit Ratio 'Recyclability$_{\text{,Benefit}}$' [%]				

3.5.3 The Energy Recoverability Benefit Ratio

Formula 3 introduced the 'Energy Recoverability Ratio' ($ER_{Recovery}$) expressed as fraction in mass of the product that is potentially recoverable by incineration. This formula can be modified by introducing the **Energy Recoverability Benefit Ratio**' ($\boldsymbol{ER_{Benefit,Ratio}}$) [%]:

'**Energy Recoverability Benefit Ratio**' (***ERecoverability$_{Benefit}$***) [%]: it is the ratio between the environmental benefits related to the potential energy recovery of the product (or its parts) by incineration, with the maximum benefits that is potentially achievable by incineration. It is calculated as:

Formula 29 $$ERecoverability_{\text{Benefit}} = \frac{ER_{Benefit}}{ER_{Benefit,Max}} \cdot 100$$

Where:

$$\text{ER}_{\text{Benefits}} = \eta \cdot I \cdot \sum_{i} \sum_{i} D_{i,k} \cdot C_{2_{i,k}} \cdot m_{i,k} \cdot \frac{\text{HV}_{\text{i,k}}}{3.6}$$

$$\text{ER}_{\text{Benefits, Max}} = \eta \cdot I \cdot \sum_{i} \sum_{i} m_{i,k} \cdot \frac{\text{HV}_{\text{i,k}}}{3.6}$$

- $\text{ER}_{\text{Benefit}}$ = Potential environmental benefit related to the potential energy recovery of the product [unit];
- $\text{ER}_{\text{Benefit,Max}}$ = Potential maximum potential environmental benefit related to the energy recovery of the product [unit];
- All the other symbols are those already introduced in Chapter 2.5 and Chapter 3.4.1.

For example, for illustrative purposes, it could be assumed that:

- η = 0.3 (Efficiency factor for the production of electricity from an incineration plant).
- 'I' = 0.59 [kg CO_{2eq}/kWh] (GWP related to the production of 1 kWh of "EU-27 Electricity Mix AC; consumption mix, at consumer; < 1kV" [ELCD, 2010]).

The formula is implemented in the calculation spreadsheet of Table 22.

Note that Formula 29 is independent from the values of the parameters 'η' and 'I', because they are both present into the numerator ($ER_{Benefit}$) and the denominator ($ER_{Benefit,Max}$). These two parameters are therefore not influencing the index but, of course, they are necessary to estimate the environmental benefit potentially achievable.

Formula 29 can be therefore applied to other different alternatives for the energy recovery. In this case, the previously introduced parameter 'ϕ' and 'ε' should be introduced in the Formula

29, and the heating value ‘HV’ of the material should be substituted with the heating value ‘HV’ of biogas or syngas.

Table 22 Spreadsheet for the calculation of the Energy Recoverability Benefit Ratio

Component		Details		Disassemblability	Contamination Index	Lower Heating Value [MJ/kg]	Potential recoverable energy [MJ]
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	C'_2 [%]		
				Energy conversion factor 'η'	0.3		
				Specific Environmental benefit [$kg_{CO2eq.}$/kWh]	0.59		
				Potential recoverable energy "$ER_{Potential}$"[MJ]			
				"$ER_{Benefit}$" [$kg_{CO2.eq.}$]			
				"$ER_{Benefit,Max}$" [$kg_{CO2.eq.}$]			
				Energy Recoverability Benefit Ratio "$ERecoverability_{Benefit}$" [%]			

3.5.4 Verification procedure of the ‘RRR Benefit Ratio’ indices

The verification procedure of the above introduced indices is based on self-declarations of the manufacturer supported by technical documentation available before the product is put into the market and provided on request (e.g. a check by the competent body).

The declarations related to the RRR Benefit Ratio indices could be verified e.g. by a Market Surveillance Authority (MSA) that can check the truthfulness of provided information (e.g. BOM, ‘disassembly scheme’, disassembly report) and successively would follow the calculation done by the manufacturer in the ‘calculation data sheet’.

3.5.5 Environmental indices and technology mix

The previous chapters introduced some indices for the measurement of the *RRR* potentials. However, these indices are based on some initial assumptions concerning the environmental impact due to the manufacturing of the materials, as well the technology employed for the reuse/recycle/recovery of the product/components at the EoL.

As pointed out in Chapter 2.5.5, being not possible to foresee what treatments the product will undergo, it is necessary to refer to an average ‘EU technology scenario’. Procedures for the calculation of ‘Disassemblability’, ‘Contamination’ and ‘Material Recyclability’ indices have been already introduced as well some exemplary tables with illustrative values.

The present section discusses how technological differences could influence the measurement of the *RRR* Benefit Ratio. In particular, the parameters influenced by the technology mix are:

a) *The environmental impacts related to the 'primary' production of the materials 'I' and the differential impact index 'δ'.*

The impacts related to the production of materials have been discussed in Chapter 3.3 and subsequent chapters. The assessment is based on the LCA methodology and the survey of data available in the European and also extra-European context[68].

The chapter also discussed the limits and the potential difficulties of the survey of the scientific literature (Chapter 3.3.3). It is important to grant a sufficient data quality and, in particular, the consistency among studies from different sources. *Note also that the survey has been here illustrated on the basis of only two impact categories (GWP and PEC). Different impact categories should be considered for a more comprehensive analysis*.

It is pointed out that, when available, LCA data from the ELCD [ELCD, 2010] should be adopted as representative of the average European technology context. The consistency among other considered studies should be granted for example by the compliance to the ILCD handbook [ILCD, 2010].

Analogously, the differential impact index 'δ' of Formula 17 is based on LCA data concerning the production of primary and recycled materials. The calculation of the index 'δ' follows the same steps of the calculation of the index 'I'. The calculated values of the differential indices can be considered as an estimation of the potential environmental benefits.

Table 19 and Annex II illustrated the results of the scientific survey performed on the scientific literature. However, the study regarded only a limited set of material commonly used into EuP. Furthermore, the survey revealed a general lack of data especially concerning the production of secondary materials. The values in Table 19 should therefore be assumed as illustrative of the proposed methodology**.**

It is important to underline that the indices '*I*' and 'δ' can be calculated on the basis of different impact category. The present study limited the assessment to the emissions of greenhouse gases and the consumption of primary energy, but other more comprehensive impact categories could be selected.

A procedure for the calculation of the indices '*I*' and 'δ' includes:

- to identify the set of materials that have to be investigated;
- to check the availability of LCA data about the primary and secondary production of the identified materials. When available, data form the ELCD should be adopted. Otherwise, other suitable references should be identified (e.g. LCA databases, scientific publications, Environmental Product Declarations, etc.), granting a sufficient quality of data (the

[68] The extraction, refining and manufacturing of some materials (e.g. rare earth or precious metals) are, in some case, restricted to very specific regions outside the Europe. In this case the survey of used technology should also include the analysis of extra-EU production contexts.

investigated process should be considered representative of the EU context) and consistency among different studies. Consistency should be granted by the compliance to the ILCD handbook [ILCD, 2010];

- to identify one (or more) environmental impact category for the calculation of the indices;
- to calculate the index '*I*' as life-cycle impact related to primary and secondary production of the identified materials.
- to calculate the index 'δ' as in Formula 17.

b) *The factors related the energy conversion during the recovery 'η', 'ϕ' and 'ε'.*

Chapters 3.4.1 and 3.5.3 illustrate how to calculate the environmental benefits related to the energy recovery. It has been shown that, independently from the selected typology of recovery alternative, formulas for the calculation of the benefits have a similar structure.

In particular, the calculations refer to some energy conversion factors ('η' for incineration, 'ϕ'for anaerobic digestion and 'ε' for gasification/pyrolysis) and to the physical/chemical characteristic of the outputs of the recovery process (e.g. heating value and composition of the biogas, syngas, char).

As noted previously, being the proposed measurement methodologies applied at the Design stage, it is not possible to foresee what treatment they product will undergo. Therefore, the methodology is based on some initial assumptions about an average recovery treatment of the product at the EoL.

Even a scenario based on a mix among the different technologies could be feasible. For example it could be assumed an average scenario where it is supposed that the waste could be addressed both to incineration (with a share of X%), gasification (share of Y%) and pyrolysis/gasification (share of Z%). In this case, the estimation of the benefits related to the energy recovery would refer to an average weighted value '$f_{Average}$' of the energy conversion factors, i.e.:

Formula 30 $$f_{\text{Average}} = X \cdot \eta + Y \cdot \phi + Z \cdot \varepsilon \quad [\%]$$

Where:

- f_{Average} = average weighted energy recovery conversion factor [%];
- X, Y, Z = share of the material that would be addressed to, respectively, incineration, anaerobic digestion, and gasification/pyrolysis [%];
- 'η', 'ϕ', 'ε' = energy conversion factors for recovery by, respectively, incineration, anaerobic digestion, and gasification/pyrolysis [%];

'η', 'ϕ' and 'ε' should be calculated as explained in Chapters 3.4.1, considering average value of efficiency of plants for the energy recovery by incineration, anaerobic digestion, and gasification/pyrolysis.

X, Y, Z should be estimated on the base of the technology mix that is currently applied in the EU, or how it is expected to develop in a next future.

It is pointed out that:

- The main focus of the present project is on EuP and materials embodied into EuP;
- Recovery by incineration is currently the most widespread technology for the energy recovery of the waste from EuP;
- Biodegradable substances embodied into EuP are limited and, mostly, concerning paper/cardboard used for packaging. For this reason, energy recovery by anaerobic digestion is assumed not relevant;
- Energy recovery by gasification/pyrolysis of some materials embodied into EuP (e.g. plastics and paper/cardboard) is feasible. However, as discussed in Deliverable 1, such technologies are still not largely used in the EU. Even in the scientific literature there is not a concordant opinion about the potential benefits and impacts related to their use. Few LCA studies of these technologies have been currently carried out.

Based on these considerations, the case-study analysis of the present report will refer only to the energy recovery by incineration. The extension to other energy recovery options is however potentially feasible as above described.

3.6 Illustration of RRR Benefit Ratio applied to an exemplary coffee-maker

The previous chapter introduced the indices for the calculation of the benefits related to the potential reuse, recycle and energy recovery of a product. These indices will be here applied to an exemplary 'coffee-maker' (Chapter 1.4).

The values of the 'disassemblability', material degradation and contamination index are those already calculated in Chapter 2.8 and shown in Table 16.

The environmental benefits will be estimated in terms of saved emission of greenhouse gases (expressed as of kg CO_{2eq}). Results are shown in Tables 23, 24 and 25. It is estimated that:

- the reusability benefit ratio amounts to 3.2%. The potential benefits related to reuse amount to the saving of 0.34 kg CO_{2eq}.;
- the recyclability benefit ratio amounts to 59.9%. The potential benefits related to recycle amount to the saving of 5.1 kg CO_{2eq};
- the Energy recoverability benefit ratio amounts to 75.1%. The potential benefits related to recycle amount to the saving of 1.01 kg CO_{2eq}.

Readers should be not surprised that the reuse grants 'apparently' lower benefits than recycle/recovery. Reusable components are, in fact, a small part of all the product's components. A consistent comparison should regard the same component that is potentially recoverable, recyclable and reusable.

For example, let consider the plastic handle of the carafe of the coffee-maker. The potential environmental befits are:

- Potential benefits related to reuse: 0.22 kg CO2eq.;
- Potential benefits related to recycle: 0.13 kg CO2eq.;
- Potential benefits related to energy recovery: 0.073 kg CO2eq[69].

It is possible to observe that reuse is the best option; its benefits are more than double compared to the recycling and about for times compared to the energy recovery.

Furthermore, it should be considered that a recyclable product could be successively recovered, and that a reusable part could be further recycled and recovered. Differences among the benefits related to *RRR* would be therefore furthermore accentuated.

[69] Value calculated as the product of the feedstock energy of the plastic handle (1.49 MJ= 0.42 kWh) multiplied by the energy efficiency of the incineration (0.3) and by the specific impacts for the production of electricity (0.59 kg_{CO2eq}/kWh)

Table 23 Illustrative spreadsheet for the calculation of the Reusability Benefit Ratio

Component		Details		Disassemblability	Material Degradation	Impact for primary production	Potential benefits related to reuse
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	M_D [%]	I_{GWP} [kg CO2eq./kg]	[kg CO2eq.]
Plastic handle	1.1	Polycarbonate (PC) (*)	0.05	100%	56%	7.76	0.22
Glass pot	1.2	Glass	0.5	100%	25%	0.77	0.10
		Steel (screws)	0.01	100%	100%	2.98	0.03
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS) (*)	0.05			3.87	
Framework /supports	3.1	Steel	0.08			2.98	
		Steel (screws)	0.01			2.98	
Metal heating plate	3.2.1	Copper	0.1			3.2	
		Steel (screws)	0.04			2.98	
Resistive heating element	3.2.2	Copper	0.06			3.2	
Wires	4	Copper	0.075			3.2	
		Polypropylene (PP)	0.025			2.33	
Sensors/ fuses	5	Various (metals, glass)	0.02			-	
Printed Circuit Board	6	Copper	0.03			3.2	
		Steel	0.02			2.98	
		Aluminum	0.04			9.67	
		Glass-reinforced plastic (***)	0.03			4.96	
		Other	0.01			-	
		Steel (screws)	0.01			2.98	
Pipes	7.1	Aluminum	0.6			9.67	
Insulations	7.2	Polypropylene (PP)	0.05			2.33	
Switches	8	Copper	0.01			3.2	
		Polycarbonate (PC) (*)	0.04			7.76	
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS) (*)	0.3			3.87	
Packaging	10	Low Density Polyethylene (PE-LD)	0.01			2.1	
		Corrugated Cardboard	0.4			0.679	
User's Manuals	11	Paper	0.03			0.97	
						$Reuse_{Benefit}$ [kg CO2eq.]	0.34
						$Reuse_{Benefit,Max}$ [kg CO2eq.]	10.66
						Reusability Benefit Ratio "$Reusability_{Benefit}$" [%]	3.23%

(*) GWP for primary production of polycarbonate amounts to 7.76 kg CO2eq./kg (from [ELCD, 2010])
(**) GWP for primary production of ABS amounts to 3.87 kgCO2eq./kg (from [ELCD, 2010])
(***) GWP for primary production of glass fibre reinforced plastic (with polyester resin) amounts to 4.96 kgCO2eq./kg (from [Ecoinvent 2.0])

Table 24 Illustrative spreadsheet for the calculation of the Recyclability Benefit Ratio

Component		Details		Disassemblability	Contamination Index	Material Degradation	Differential impact	Potential benefits related to recycling
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	C'_1 [%]	M_R [%]	δ_{GWP} [kg CO2eq./kg]	[kg CO2eq.]
Plastic handle	1.1	Polycarbonate (PC) (*)	0.05	98%	100%	77%	3.54	0.13
Glass pot	1.2	Glass	0.5	98%	0%	75%	0.24	0
		Steel (screws)	0.01	98%	100%	100%	2.16	0.02
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS) (*)	0.05	98%	100%	84%	2.44	0.10
Framework /supports	3.1	Steel	0.08	84%	100%	100%	2.16	0.15
		Steel (screws)	0.01	84%	100%	100%	2.16	0.02
Metal heating plate	3.2.1	Copper	0.1	72%	100%	100%	2.76	0.20
		Steel (screws)	0.04	72%	100%	100%	2.16	0.06
Resistive heating element	3.2.2	Copper	0.06	72%	100%	100%	2.76	0.12
Wires	4	Copper	0.075	71%	50%	100%	2.76	0.07
		Polypropylene (PP)	0.025	0%	50%	81%	1.22	0
Sensors/ fuses	5	Various (metals, glass)	0.02				-	0
Printed Circuit Board	6	Copper	0.03	68%	50%	100%	2.76	0.03
		Steel	0.02	76%	50%	100%	2.16	0.02
		Aluminum	0.04	72%	50%	100%	9.17	0.13
		Glass-reinforced plastic	0.03	0%	50%	0%	-	0
		Other	0.01	0%	50%	0%	-	0
		Steel (screws)	0.01	76%	100%	100%	2.16	0.02
Pipes	7.1	Aluminum	0.6	66%	100%	100%	9.17	3.63
Insulations	7.2	Polypropylene (PP)	0.05	66%	100%	81%	1.22	0.03
Switches	8	Copper	0.01	56%	50%	100%	2.76	0.01
		Polycarbonate (PC) (*)	0.04	0%	50%	77%	3.54	0.00
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS) (*)	0.3	66%	75%	84%	2.44	0.30
Packaging	10	Low Density Polyethylene (PE-LD)	0.01	100%	100%	71%	1.2	0.01
		Corrugated Cardboard	0.4	100%	100%	16%	0.12	0.01
User's Manuals	11	Paper	0.03	100%	100%	16%	0.46	0.002
							$Recycle_{Benefit}$ [kg CO2eq.]	5.1
							$Recycle_{Benetit,Max}$ [kg CO2eq.]	8.5
							Recyclability Benefit Ratio '$Recyclability_{,Benefit}$' [%]	59.9%

(*) Data about differential impacts for Polycarbonate and ABS are not available. It is supposed that the differential index for Polycarbonate is equal to that of Polistyrene while the differential index of ABS is equal to Polyethilene.

Table 25 Illustrative spreadsheet for the calculation of the Energy Recoverability Benefit Ratio

Component		Details		Disassemblability	Contamination Index	Lower Heating Value [MJ/kg]	Potential recoverable energy [MJ]
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	C'2 [%]		
Plastic handle	1.1	Polycarbonate (PC)	0.05	98%	100%	30.4	1.49
Glass pot	1.2	Glass	0.5				
		Steel (screws)	0.01				
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS)	0.05	98%	100%	38	1.86
Framework /supports	3.1	Steel	0.08				
		Steel (screws)	0.01				
Metal heating plate	3.2.1	Copper	0.1				
		Steel (screws)	0.04				
Resistive heating element	3.2.2	Copper	0.06				
Wires	4	Copper	0.075				
		Polypropylene (PP)	0.025	42%	50%	46.2	0.24
Sensors/ fuses	5	Various (metals, glass)	0.02				
Printed Circuit Board	6	Copper	0.03				
		Steel	0.02				
		Aluminum	0.04				
		Glass-reinforced plastic (*)	0.03	40%	50%	8	0.05
		Other	0.01				
		Steel (screws)	0.01				
Pipes	7.1	Aluminum	0.6				
Insulations	7.2	Polypropylene (PP)	0.05	66%	100%	46.2	1.52
Switches	8	Copper	0.01				
		Polycarbonate (PC)	0.04	33%	50%	30.4	0.20
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS)	0.3	66%	100%	38	7.52
Packaging	10	Low Density Polyethylene (PE-LD)	0.01	100%	100%	42	0.42
		Corrugated Cardboard	0.4	100%	100%	16.9	6.76
User's Manuals	11	Paper	0.03	100%	100%	18.4	0.55

Energy conversion factor 'η'	0.3
Specific Environmental benefit [kg $CO2_{eq.}$/kWh]	0.59
Potential recoverable energy "$ER_{Potential}$"[MJ]	6.19
"$ER_{Benefit}$" [kg $CO2_{.eq.}$]	1.01
"$ER_{Benefit,Max}$" [kg $CO2_{.eq.}$]	1.35
Energy Recoverability Benefit Ratio "$ERecoverability_{Benefit}$" [%]	75.1%

(*) Lower Heating Value of Glass-reinforced plastic was supposed 8 [MJ/kg], assuming a 33% content of polyester resins (LHV 24 MJ/kg)

3.7 Summary

The present chapter describes how life-cycle data of materials can be introduced into the prioritisation of the resources, and how the results can be put in relation with the previous methodologies for the measurements of *RRR*.

According to the scopes of the project, the attention has been focused on the *RRR* and the potential benefits related to the reuse/recycling/recovery of the materials as a key issue for their prioritisation.

For example it has been defined the <u>*differential impact* δ</u> *that represents the difference among the impact to produce one unit of primary material and that to produce the same quantity from recycled scraps. As bigger is such differential, as higher is the potential environmental 'benefit' related to the recycling.*

Analogously, the benefits related to the full or partial reuse of a product can be estimated in terms of avoided manufacturing of new components. The benefits due the energy recovery can be estimated in terms of avoided use of conventional energy carriers.

The proposed methodology for the resource prioritisation can be potentially applied referring to any life cycle impact category. The methodology has been here illustrated only on two selected impact categories. It is important to remind that the selection different reference impact categories could leas to very different results;

Successively Chapter 3.5 introduces a methodology to integrate the prioritization of resources with the calculation of the Reusability, Recyclability and Energy Recoverability. In particular, it is described a procedure to estimate the potential environmental benefits related to the potential reuse, recycle or recovery of products. Finally Chapter 3.7 illustrates an application of the proposed methodology to the 'coffee-maker' example of Chapter 1.4 and 2.8.

Concerning the energy recovery, the potential benefits related to incineration are estimated. Other recovery options (anaerobic digestion, pyrolysis, gasification) have been also investigated. It was observed that the methodology for the assessment of benefits due to the energy recovery is also suitable for other considered recovery options. Therefore, the Recoverability Benefits index is potentially extensible to other recovery alternatives.

However, Chapter 3.5.5 observes that anaerobic digestion is generally not relevant for materials generally used for EuPs. Note also that pyrolysis/gasification plants are not largely diffused in the EU. Furthermore, few LCA studies about pyrolysis/gasification plants have been presented in the scientific publications and the scientific community is still debating on the potential benefits related to these treatments. For these reasons, the case-study analysis of the following chapters will focus the attention on the energy recovery by incineration.

4 A method for the measurement of the 'recycled content'

4.1 Introduction

The 'recycled content' is generally defined as the "*proportion, by mass, of recycled material in a product or packaging*" [ISO 14021, 199]. As shown in Deliverable 1, there is a general agreement on such definition in several international standards.

Differently from the 'reusability', 'recyclability' and 'recoverability' that are a 'potentials' of the product, the 'recycled content' is a physical property related to the manufacturing 'history' of the product and all its components. Once a product is realized, its recycled content is fixed and this does not change over the time (despite, for example, of the recyclability that can change in function of the evolution of the recycling technologies).

Unfortunately, the recycled content cannot be directly measured but it can be only indirectly estimated. "*As there are no methods available for directly measuring recycled content in a product or packaging, the mass of material obtained from the recycling process, after accounting for losses and other diversions, shall be used*" [ISO 14021, 1999].

The present Chapter will illustrate a methodology for the estimation and verification of the recycled content based on the analysis of the design and manufacturing documentation.

4.2 Recycled content of a material and of a product

The recycled content '$r_{Content}$' [%] of a component can be calculated as:

Formula 31 $$r_{Content} = \frac{m_{recycled}}{m_{tot}} \cdot 100$$

where: $m_{recycled.}$ = mass of recycled material used to manufacture the component [kg]

$m_{tot.}$ = mass of manufactured material [kg]

The recycled content '$r_{Content}$' is generally calculated from data about the input/output mass flows occurring during the manufacturing.

For example, a steel firm can estimate the recycled content of its production as the ratio between the annual input in the factory of steel scraps and the total amount of produced steel[70].

The recycled content '$R_{Content}$' [%] of a complex multi-material component or product can be analogously calculated:

Formula 32 $$R_{Content} = \frac{\sum_i m_i \cdot r_{Content,i.}}{\sum_i m_i} \cdot 100$$

where: $m_{i.}$ = mass of the ith material of the product/component [kg]

$r_{Content,i}$ = recycled content of the ith material [%];

Due to the uncertainties of the estimations, manufacturers/designers should also declare the uncertainty range of the recycled content.

4.2.1 Procedure for the calculation and of the recycled content

To calculate the recycled content, the manufacturer has (Figure 14):

1. To identify the materials constituting the product and their masses. This information can be derived from the BOM, as already described into Chapter 1;
2. To distinguish between materials that are self-manufactured and those purchased by suppliers. Two cases are viable:
   - If the material is purchased, the manufacturer has to collect data from the suppliers, obtaining indication about the recycled content;
   - If the material is self-produced, the manufacturer has to collect data about the related production process. The needed data concern the quantity of recycled scraps used for the manufacturing and the total quantity of the output material (Formula 31). Being the methodology already applicable at the design stage, the manufacturing process could be not activated yet. Manufacturer can refer to similar production processes already undergone or, when the process is totally new designed, to the expected input/output flows. In this last case, the estimation has to be corrected/reviewed after the production starts. Data should refer to a sufficient monitored period (not lower than 12 months).
3. To use the masses and recycled content of the materials to calculate the overall product 'recycled content' (formula 29).

[70] Several associations compute the annual recycled content ratio for some specific materials, based on regional, national or international statistics. For example the World Steel Association (www.worldsteel.org), the former International Iron and Steel Institute – IISI, computes the recycling rate and the recycled content of several steel products based on the input data of hundreds of manufacturers all around the world.

An exemplary spreadsheet for the calculation of the ‘recycled content’ is shown in Table 26.

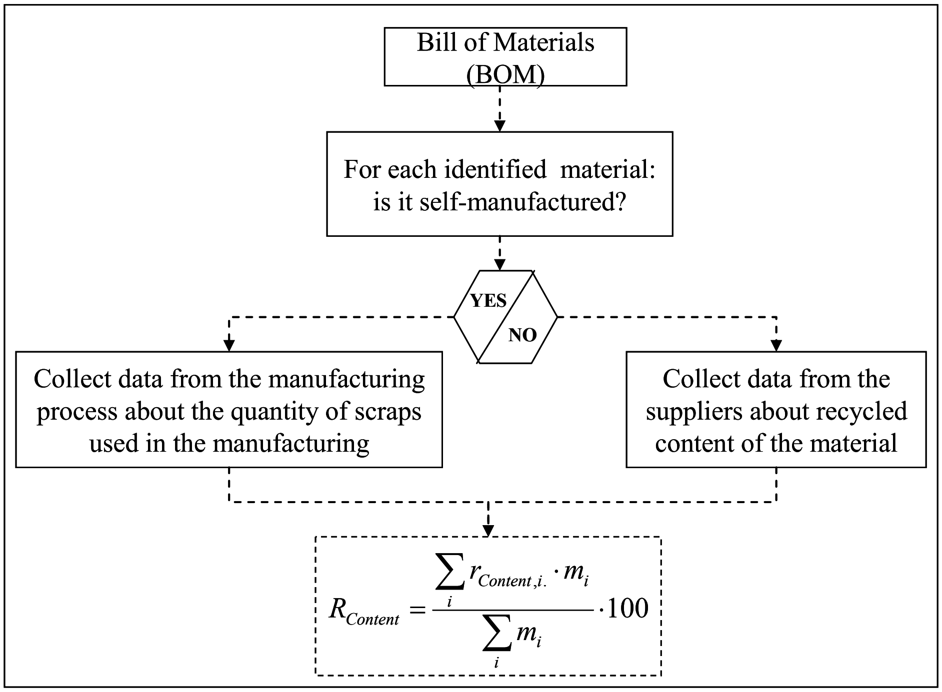

Figure 14 Procedure for the calculation of the Recycled content of a product

Table 26 Example of spreadsheet for the calculation of the Recycled Content ‘$R_{Content}$’

Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	Has the material a recycled content? [YES/NO]	Is the material self-manufactured? [YES/NO]	Material recycled content '$r_{Content}$' [%]	'$r_{Content}$' * m_i [kg]
						Σ ($r_{content}$ * m_i) [kg]		
Total mass "m_{tot}" [kg]						**$R_{Content}$ [%]**		

4.3 Pre-consumers and post-consumers recycling

The deliverable 1 discussed the different role of 'pre-consumers' and 'post-consumers' recycled content of the products [ISO 14021, 1999]:

- *Pre-consumer material*: Material diverted from the waste stream during a manufacturing process. Excluded is reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it.
- *Post-consumer material*: Material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose. This includes returns of material from the distribution chain.

In some labelling schemes also Ecodesign requirements are differentiated between pre-consumers and post-consumers recycled content, focusing mostly on this last. Post-consumers recycling is, however, more difficult to accomplish and it relates also to the behaviour of final users.

The methodology for the calculation of pre-consumers and post-consumers recycled content is similar to that already introduced in Chapter 4.2.1. The only difference is that the calculation has to be differentiated into the two contributions. The new formulas are:

Formula 33 $$R_{Content,PRE} = \frac{\sum_i m_i \cdot r_{Content,PRE,i.}}{\sum_i m_i} \cdot 100$$

Formula 34 $$R_{Content,POST} = \frac{\sum_i m_i \cdot r_{Content,POST,i.}}{\sum_i m_i} \cdot 100$$

where: '$R_{Content,PRE}$' = Pre-consumers recycled content [%];

'$R_{Content,POST}$' = Post-consumers recycled content [%];

$m_{i.}$ = mass of the ith material of the product [kg];

$r_{Content,i,PRE}$ = pre-consumers recycled content of the ith material [%];

$r_{Content,i,POST}$ = post-consumers recycled content of the ith material [%].

For a given product, the three indices of Formula 32, Formula 33 and Formula 34 are connected by the following relation:

Formula 35 $$R_{Content} = R_{Content,PRE} + R_{Content,POST}$$

4.4 Ecodesign requirements about the recycled content

As defined in Chapter 3.2, the recycled content can concern the full product or a part of it. In particular, it could concern a specific material (e.g. recycled content of iron) or a sub-assembly or any accessory component (e.g. recycled content of the framework or of some plastic components). Consequently, Ecodesign requirements could be set for the entire product (i.e. related to the average recycled content of the product) or for some specific parts (e.g. minimum content of recycled mass into plastic components).

This distinction among the requirements is very important. In fact, the recycling rates of materials differ largely. For example, the recycling of metals is generally much higher than the recycling of plastics; this is due to the physical properties of the materials and also to economic costs/revenues related to the recycling.

The survey of Deliverable 1 observed that the majority of requirements about the recycled content of products have been focused on the plastic components[71]. The requirements on the recycled content aim to boost the collection and treatment of post-consumers waste, to increase their 'desirability' and their re-introduction into new manufacturing processes.

4.4.1 How to set requirements about the recycled content of materials?

An important issue concerning the establishment of potential recycled content requirements is the identification of the target materials. This topic was also discussed in the ILCD Handbook [EC, 2010]:

"*In markets that are growing or where for other reasons (e.g. "green image") the demand for a secondary good is higher than the amount that is available via recycling/reuse/recovery (e.g. in most but not all current material markets), the main necessity is obviously to increase the recycling rate […] and not the demand for recycled materials (i.e. recycled content).*

A comparatively high market price of the secondary good compared to the price of the same primary good means at least one of the following:

- the market is growing and the recycled material is of sufficient / high quality and/or

- there is demand for the secondary good for other reasons (e.g. positive "green" perception)

In consequence, mainly the quantitative extent of reuse/recycling/recovery needs to be promoted […].

A comparatively low price of the secondary good (compared to the one of the primary produced good) indicates at least one of the following:

- there is a high recycling rate for some reason that provides an excess of the secondary good, and/or

[71] We refer to requirements set by some technical standard or product labelling schemes. For further details, see Deliverable 1 – Chapter 3.

- the achieved technical quality of the secondary good is low […] and/or

- there is a limited demand for the secondary good for other reasons (e.g. "waste-image" perception, hygiene legislation, etc.).

If the amount that is available via reuse/recycling/recovery is higher then the demand, and the market value is accordingly below zero, the main necessity is to increase the demand for the secondary good (i.e. recycled content) and/or its technical quality […], but not the simple recycling rate […]" [EC, 2010].

The value of recycled materials is therefore a parameter useful to identify the target materials whose recycling needs to be stimulated via 'recycled content' requirements. In particular, it is important to consider the ratio between the value of the secondary material and the value of the primary material (similarly to the index already introduced in Chapter 2.5.4.2).

If a material has a high value after recycling, it is probable that it will be recycled. Companies will also try to divert such material from the waste flows and to address it to a recycling facility. A requirement about the recycled content could be therefore useless or, in some case, counterproductive.

For example, let consider a steel components. As discussed in Chapter 2, secondary steel is characterized by high quality and high economic value. Therefore steel components are recycled every time that it is viable (i.e. the steel component is not contaminated and easy to disassembly). Very high levels of recycling rates of steel are already achieved[72]. The setting of requirements about a minimum of recycled content of steel probably would not boost more the recycling. This activity, in fact, already tries to achieve the best recycling rate, depending on the availability of secondary scraps. The improvement of the recycling of steel should, instead, be related to the improvement of the recyclability of the steel components.

On the other side, low values of the secondary goods can be related to a limited demand or to a low quality of the material (due to changes of its physical/chemical inherent properties). The introduction of recycled content requirements could have, therefore, the effects to stimulate the demand and, at the same time, to stimulate the technological progress for the recycling of such material.

For example, Annex 1 showed that paper and cardboard are characterized by low values after recycling. This circumstance does not encourage the recycling of the materials after their use. The adoption of recycled content requirements could have the effect of encouraging the collection and recycling of paper and cardboard after their use. We also underline that various labelling and certification schemes[73] already introduced some requirements about the recycled content of cardboard/paper and plastic.

For example, it is here presented a requirement about the recycled content of packaging for EEE [IEEE, 2009]:

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[72] For example, the Worldsteel Institute estimated that in 2007 the average recycled content of steel amounted to about 83% (source: Worldsteel at website: www.worldsteel.org/pictures/programfiles/Fact%20sheet_3Rs.pdf access on November 2010)

[73] For example, the EU Ecolabel, the Nordic Swan, or the standards IEEE1680.1 for the environmental assessment of electronic products.

"***Requirement****: Packaging shall meet or exceed the minimum postconsumer content for respective packaging in the U.S. EPA Comprehensive Procurement Guidelines - CPG*[74] *over the course of a year using a weighted average.*

Applies to*: Packaging of products that are declared to conform to this standard.*

Verification requirements*:*

a) Declaration from manufacturer;

b) Supplier letter;

c) Designation of the Comprehensive Procurement Guidelines that is met".

4.4.2 Recycled Content of priority resources

Chapter 4.4.1 discussed the setting of potential requirements about the recycled content of specific materials. The scope of such requirements is to boost the recycling of some materials that nowadays are instead generally incinerated or disposed to landfills.

Requirements could be set concerning the identified critical materials (e.g. those with higher value of indices δ *and* Δ in Table 19). The scope would be therefore to promote the recycling of those materials that can grant relevant reduction of the emission of pollutants when recycled.

The potential requirements could also concern materials that have been identified as 'priority' for different reasons (for example those materials that have been identified by the European study on Critical raw materials, discussed in Chapter 3.1). In this context, requirements about the recycled content could contribute to improve the recycling of priority materials and, in this way, contribute to reduce the risks related to the material supply. Critical materials listed in Table 18can be, for example, the potential target for 'recycled content' requirements.

4.4.3 Verification of the recycled content claims

The verification of the recycled content claims is based on self-declaration of the manufacturer supported by technical documentation e.g.material flows declaration or chain of custody declaration from manufacturer and its suppliers.

The documentation has to be available before the product is put into the market and provided on request (e.g. a check by the competent body) .

[74] U.S. EPA recommended recovered fibres content levels for paperboard and packaging products.

4.5 Calculation of the recycled content: a case-study

The above described methodology has been applied to the case-study product of Chapter 2.8. The calculation refers only to '*post-consumer' recycled content*.

For the calculation, the manufacturer of the coffee-maker declares that the heating plate and resistive heating (copper), the framework (steel), the pipes (aluminium), the glass pot (carafe), the packaging (cardboard) and the manuals (paper) have a recycled content. Plastic housing/framework, plastic packaging and pipe insulation, instead, do not contain recycled materials. No data are available concerning the Printed Circuit Boards, the switches, the fuses, the wires and the screws: therefore it is assumed that they have a null recycled content.

It is supposed that, concerning the provision of materials:

- Copper plate and resistive heating are purchased. From the documentation of suppliers, the recycled content of the steel plate is 40%;
- Aluminium pipes are purchased. From the documentation of suppliers, the recycled content of the steel plate is 60%;
- The steel framework parts for the heating systems are purchased. From the documentation of suppliers, the recycled content of the steel plate is 30%;
- Cardboard packaging and paper for manuals are also purchased. Suppliers declare that 30% of cardboard and 100% of paper are from recycled fibres;
- Glass carafe is instead self-manufactured by the company. On this purpose the company declare that it already produces other similar glass components. In the production process the company use post-consumer glass scraps (coming from the urban waste collection system) that are re-melted (with new silica and other additives) to produce new glass pots. The manufacturer estimates that glass carafe has 50% post-consumer recycled content[75].

The calculation data-sheet of the recycled content is then showed in Table 27. *The Recycled content index of the coffee-maker results 32.6 % in mass*.

Concerning the verification process, the manufacturer has to provide the following documentation:

- declaration of the suppliers concerning the assumed values of recycled content;
- Input/output mass flows concerning the recycling of glass scraps and the production of new glass. Company should provide the documentation that proves that 50% of the mass of new glass products is originated by recycled scraps. Data should be based at least on the time length of one year with a detail of the used mass of scraps. The calculated recycled content for self-manufactured materials should be periodically updated.

[75] Note that glass pot is not recyclable (due to the presence borosilicate, as discussed in Chapter 2.5.3), but it has however a recycled content. Recycled content and recyclability are in fact two distinct concepts.

Table 27 Example calculation of the Recycled content for the case-study of the electrical heater

Component		**Details**			**Recycled content '$R_{Content}$'**			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	Has the material a recycled content? [YES/NO]	Is the material self-manufactured? [YES/NO]	Material recycled content '$r_{Content}$' [%]	'$r_{Content}$' * m_i [kg]
Plastic handle	1.1	Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.05	NO			
Glass pot	1.2	Glass	Borosilicate heat resistant glass: Boron (B) content: 4%	0.5	YES	YES	50%	0.25
		Steel	Screws	0.01	data not available			
Upper/lower covers	2	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A (0.05%)	0.05	NO			
Framework /supports	3.1	Steel		0.08	YES	NO	30%	0.024
		Steel	Screws	0.01	data not available			
Metal heating plate	3.2.1	Copper		0.1	YES	NO	40%	0.04
		Steel	Screws	0.04	data not available			
Resistive heating element	3.2.2	Copper		0.06	YES	NO	40%	0.024
Wires	4	Copper		0.075	data not available			
		Polypropylene (PP)	Combustible-LHV:46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.025	data not available			
Sensors/ fuses	5	Various (metals, glass)		0.02	data not available			
Printed Circuit Board	6	Copper		0.03	data not available			
		Steel		0.02	data not available			
		Aluminum		0.04	data not available			
		Glass-reinforced plastic	Potential combustible but with low feedstock content	0.03	data not available			
		Other		0.01	data not available			
		Steel	Screws	0.01	data not available			
Pipes	7.1	Aluminum		0.6	YES	NO	60%	0.36
Insulations	7.2	Polypropylene (PP)	Combustible - LHV: 46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.05	NO			
Switches	8	Copper		0.01	data not available			
		Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.04	data not available			
External housing / water reservoir	9	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A(0.05%); Painted and labeled parts	0.3	NO			
Packaging	10	Low Density Polyethylene (PE-LD)	Combustible - LHV: 42 MJ/kg; Flame ret.: Red Phosphorus	0.01	NO			
		Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg	0.4	YES	NO	30%	0.12
User's Manuals	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.03	YES	NO	100%	0.03
							Σ ($r_{content}$ * m_i) [kg]	0.848
			Total mass "m_{tot}" [kg]	**2.6**			**$R_{Content}$ [%]**	**32.6%**

4.5.1 Recycled content of specific materials

As discussed in Chapter 4.4, it is possible to calculate the recycled content of specific components or materials (e.g. the content of recycled material included into the packaging has been calculated).

Assuming the same hypothesis of the previous paragraph, cardboard into packaging has a recycled content of 30% while PE-LD has not a recycled content. Therefore, considering the calculation spreadsheet of Table 27, it results that:

- the overall mass of the packaging $m_{Packaging}$ amounts to 0.41 kg;
- the mass of the recycled cardboard $m_{recycled}$ amounts to 0.12 kg.

Applying Formula 31, it results that the recycled content of packaging $R_{Packaging}$ is:

Formula 36 $$R_{Packaging} = \frac{m_{recycled}}{m_{Packaging}} \cdot 100 = \frac{0.12}{0.41} \cdot 100 = 29.3\%$$

4.6 Summary

Differently from recyclability, reusability and recoverability, the recycled content is an inherent property of the product, which does not change over the time. Unfortunately this cannot be directly measured. It can be only indirectly estimated on the basis of the manufacturing history of the product.

The Chapter 4.2 introduces a methodology for the estimation of the recycled content of materials and product. The recycled content of a component is calculated as the ratio of the scraps used to manufacture the component, divided by the total mass of the component itself. When different materials are used to manufacture the component, the recycled content is the weighted mean of the recycled contents of each material. The verification of the recycled content claim is based on a self-declaration supported by technical documentation.

A further distinction can be made between ‘pre-consumer’ and ‘post-consumer’ recycled content. Although it is possible to specify a recycled content index for both, the attention should mainly focus on post-consumer recycling.

Potential Ecodesign requirements could be set concerning the recycled content of a product. The requirements could regard the ‘full product’ or some specific materials or components (e.g. the recycled content of plastics in a product). These specific requirements could contribute to boost the recycling of such materials, when it is proved that large benefits can be achieved via their recycling.

In particular, Chapter 4.4.1 discusses that requirements about the recycled content should mainly regard materials that have a low value after the recycling. Such potential requirements could contribute to increase the demand of recycled material and could also boost the technology development for the recycling of such material.

Finally Chapter 4.5 applies the proposed methodology to the measurement of the post-consumer recycled content of the coffee-machine case-study of Chapter 1.

5 Case study “hard disk”

5.1 Introduction

The present Chapter describes an application of the previously described methodologies to a case study product: a computer hard disk.

The scopes of the application are:

- to illustrate the calculation of the indices for Reusability/Recyclability/Recoverability and Recycled Content as well as assessment of the use of priority resources;
- to estimate the potentials for reuse, recycle and recovery of the product;
- to estimate the potential benefits related to the reuse/recycle/recovery of the hard disk;
- to identify some critical components of the products that could be the target of some potential design requirements.

5.2 BOM of the internal hard-disk for desktop computer

The selected case-study product is an internal hard-disk for desktop computer. Data about the product’s composition are derived from the scientific literature [Mohite, 2005].The BOM has been built on the basis of the materials breakdown and the description of the disassembly process. The BOM is shown in Figure 15 and Table 28.

The hard-disk’s mass amounts to 0.57 kg. Additional info about packaging and user’s manuals has been added. The overall mass amounts to 0.63 kg.

The BOM detail has been stopped to those components and sub-assemblies that can be considered homogeneous (hard disk, circular plates, external/internal frames, pointer assembly) and to those components that cannot be further disassembled/separated with common tools (the Printed Circuit Board) and that should be addressed to shredding. A detailed description of the Printed Circuit Board composition has been derived by data from the literature [Mohite, 2005].

Data about flame retardants, labels, and lower heating values have been estimated/assumed (information was missing from the original material breakdown). Table 29 shows a detail of the disassembly steps. Data about disassembly have been also implemented into Figure 15. The total time for disassembly amounts to 269 seconds. Data about the sub-disassembly of the hard-disk’s pointer and the circular plates have been estimated.

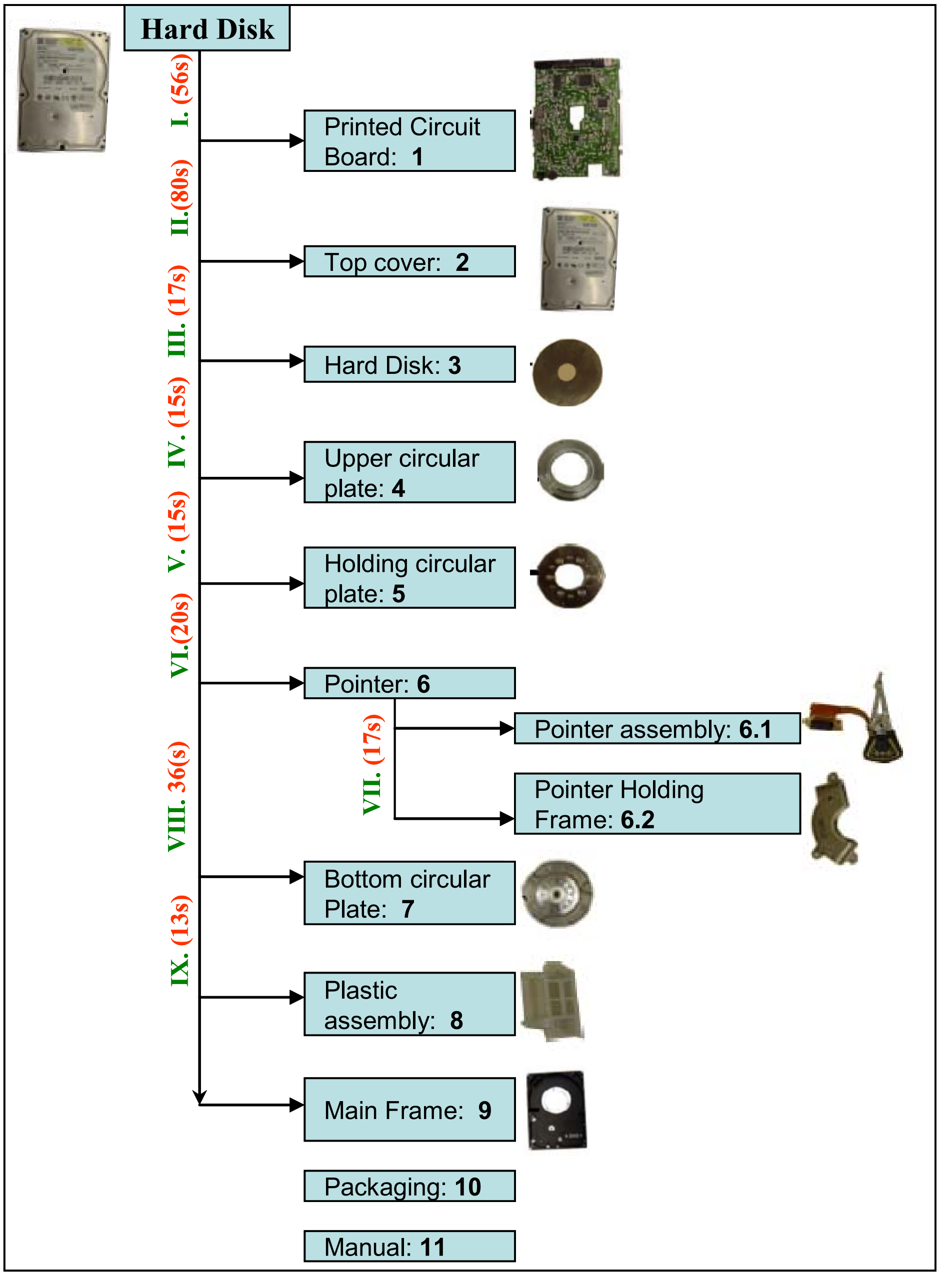


Figure 15 **Bill of Materials (BOM) of the case-study hard disk**

Table 28 Bill of Material of the case-study hard-disk

Component		Details		
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*
Printed Circuit Board	1	Glass		1.2E-02
		Copper		1.2E-02
		Epoxy Resin	Combustible-LHV: 30 MJ/kg	7.6E-03
		Ceramics		4.2E-03
		TBBP-A	Flame retardant Tetrabromobisphenol A (FR14)	3.5E-03
		Iron		1.4E-03
		Aluminium		8.5E-04
		Lead		6.4E-04
		Nickel		2.4E-04
		Barium		1.8E-04
		Zinc		3.0E-05
		Gold		2.0E-05
		Silver		2.0E-05
		Antimony		1.0E-05
		Chromium		1.4E-06
		Cadmium		1.1E-07
		Beryllium		4.7E-08
		Mercury		1.4E-09
		Steel	Screws	4.8E-04
Top Cover	2	Aluminium	Labelled (plastic adhesive label, mass <0.1%, removable and compatible with recycling)	0.12
		Steel	Screws	1.3E-03
Hard Disk	3	Aluminium		0.022
		Steel	Screws	4.8E-04
Upper circular plate	4	Aluminium		0.006
Circular plate that holds the hard disk	5	Aluminium		0.002
		Steel	Screws	3.2E-04
Pointer assembly	6.1	Aluminium		0.008
Pointer Holding Frame	6.2	Steel		0.076
		Steel	Screws	0.001
Bottom circular Plate	7	Aluminium		0.052
		Steel	Screws	4.8E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; 1% Flame ret.: Tetrabromobisphenol A (FR14)	0.001
		Steel	Screws	1.6E-04
Main Frame	9	Aluminium		0.242
Packaging	10	Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg. Inks and label are present into the package (content higher than 1%)	0.03
		PE-LD	Antistatic plastic bag. Combustible - LHV: 42 MJ/kg; Flame ret.: 2% Red Phosphorus (FR52)	0.001
		PS-E	Expanded polystyrene. Combustible-LHV: 40 MJ/kg. Flamer retardant: 0.1% Hexabromocyclododecane HBDC (FR16)	0.02
Manual	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.01
		Total product's mass [kg]		**0.637**

Table 29 Detail of Disassembly steps

Disassembly steps	Detail of the disassembly	Disassembly code of components	Disassembly action	Time for disassembly [s]
I	Extraction of the Printed Circuit Board	1	Removal of screws (3)	56
II	Opening and separation of the top cover	2	Removal of screws (8)	80
III	Removal of the Hard Disk	3	Removal of screws (5) and adhesives	17 (*)
IV	Removal of the upper circular plate	4		15 (*)
V	Removal of the circular plate that holds the hard disk	5		15 (*)
VI	Extraction of the pointer	6	Removal of screws (5)	20 (*)
VII	Separation of pointer assembly	6.1 - 6.2		17 (*)
VIII	Removal of the bottom circular plate	7	Removal of screws (3)	36
IX	Separation of plastic assembly from the main frame	9 - 9	Removal of screws (1)	13

(*) estimated time

5.3 Reusability/Recyclability/Recoverability indices of the hard-disk

The Reusability/Recyclability/Recoverability indices of Chapter 2.4 have been applied tor the case-study hard-disk.

Data from the BOM of Figure 15 and Table 28 have been implemented in the calculation spreadsheet of Table 14. Results are shown in Table 30.

Table 30 Calculation sheet for Reusability/Recyclability/Recoverability for the hard-disk case-study

Component		Details			Reusability			Recyclability				Recoverability			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass* [kg]	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{E\text{-}recovery}$	$(m_{recycle} + m_{E\text{-}recovery})$
Printed Circuit Board	1	Glass		1.2E-02											
		Copper		1.2E-02				85.0%	50%	100%	5.1E-03				5.1E-03
		Epoxy Resin	Combustible-LHV: 30 MJ/kg	7.6E-03								50.0%	50%	1.9E-03	1.9E-03
		Ceramics		4.2E-03											
		TBBP-A	Flame retardant Tetrabromobisphenol A (FR14)	3.5E-03											
		Iron		1.4E-03				95.0%	50%	100%	6.6E-04				6.6E-04
		Aluminium		8.5E-04				90.0%	50%	100%	3.8E-04				3.8E-04
		Lead		6.4E-04				80.0%	50%	100%	2.6E-04				2.6E-04
		Nickel		2.4E-04				80.0%	50%	100%	9.6E-05				9.6E-05
		Barium		1.8E-04											
		Zinc		3.0E-05				80.0%	50%	100%	1.2E-05				1.2E-05
		Gold		2.0E-05				95.0%	50%	100%	9.5E-06				9.5E-06
		Silver		2.0E-05				95.0%	50%	100%	9.5E-06				9.5E-06
		Antimony		1.0E-05											
		Chromium		1.4E-06											
		Cadmium		1.1E-07											
		Beryllium		4.7E-08											
		Mercury		1.4E-09											
		Steel	Screws	4.8E-04				100%	100%	100%	4.8E-04				4.8E-04
Top Cover	2	Aluminium	Labelled (plastic adhesive label, mass <0.1%, removable and compatible with recycling)	0.12				78%	100%	100%	9.4E-02				9.4E-02
		Steel	Screws	1.3E-03				78%	100%	100%	1.0E-03				1.0E-03
Hard Disk	3	Aluminium		0.022				76%	100%	100%	1.7E-02				1.7E-02
		Steel	Screws	4.8E-04				76%	100%	100%	3.6E-04				3.6E-04
Upper circular plate	4	Aluminium		0.01				74%	100%	100%	4.4E-03				4.4E-03
Circular plate that holds the hard disk	5	Aluminium		0.002				72%	100%	100%	1.4E-03				1.4E-03
		Steel	Screws	3.2E-04				72%	100%	100%	2.3E-04				2.3E-04
Pointer assembly	6.1	Aluminium		0.01				68%	100%	100%	5.4E-03				5.4E-03
Pointer Holding Frame	6.2	Steel		0.08				68%	100%	100%	5.2E-02				5.2E-02
		Steel	Screws	8.0E-04				68%	100%	100%	5.4E-04				5.4E-04
Bottom circular Plate	7	Aluminium		0.05				56%	100%	100%	2.9E-02				2.9E-02
		Steel	Screws	4.8E-04				56%	100%	100%	2.7E-04				2.7E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; 1% Flame ret.: Tetrabromobisphenol A (FR14)	0.001				54%	100%	84%	4.5E-04	54%	100%	5.4E-04	9.9E-04
		Steel	Screws	1.6E-04				54%	100%	100%	8.6E-05				8.6E-05
Main Frame	9	Aluminium		0.242	100%	75%	0.182	54%	100%	100%	1.3E-01				1.3E-01
Packaging	10	Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg. Inks and label are present into the package (content higher than 1%)	0.030				100%	75%	16%	3.6E-03	100%	100%	3.0E-02	3.0E-02
		PE-LD	Antistatic plastic bag. Combustible - LHV: 42 MJ/kg; Flame ret.: 2% Red Phosphorus (FR52)	0.001				100%	100%	71%	7.1E-04	100%	100%	1.0E-03	1.0E-03
		PS-E	Expanded polystyrene. Combustible-LHV: 40 MJ/kg. Flamer retardant: 0.1% Hexabromocyclododecane HBDC (FR16)	0.020				100%	100%	86%	1.7E-02	100%	100%	2.0E-02	2.0E-02
Manual	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.010				100%	100%	16%	1.6E-03	100%	100%	1.0E-02	1.0E-02
												Σ $m_{E\text{-}recovery}$		0.06	
												$ER_{Recovery}$ [%]		**10.0%**	
		Total mass "m_{tot}" [kg]		0.64	Σ m_{reuse} [kg]		0.18	Σ $m_{recycle}$ [kg]			0.37	Σ $m_{recovery}$ [kg]			0.41
					R_{Reuse} [%]		**28.5%**	**$R_{Recycle}$ [%]**			**57.5%**	**$R_{Recovery}$ [%]**			**63.9%**

5.3.1 Calculation of the Reusability ratio

Concerning the Reusability ratio 'R_{Reuse}', no data were available in the literature about the reuse of hard-disks components. However, in order to demonstrate the applicability of the methodology it is assumed that the main frame of the hard-disk would be reusable.

On such purpose we assume that the manufacturer specifically designed the component as modular, separable and suitable for remanufacturing of new hard-disk devices.

The two sub-indices needed to measure the reusability are:

- Disassemblability: from Chapter 2.5.2.1 it results D = 100% (proved that the component is specifically designed for reuse);
- Material degradation: M_D = 75%. The value comes from formula 13, assuming that:
    - $M_{D,1}$ = 100% because there are no critical standard/laws that regulate the operation of the component;
    - $M_{D,2}$ = 75% because the main frame is subjected to medium stress (thermal and physical) and because the frame has to sustain the hard disk and protect him from damages. Only frames without deformations are suitable for reuse;
    - $M_{D,3}$ = 100% because it is assumed that the behaviour of the user does not influence the component. It is, in fact, and internal component placed inside the frame of a PC and, therefore, it is generally not directly accessible and handled by the users.

The product's Reusability Ratio amounts to 28.5%.

Note that the potential for reuse is quite large (almost one third of the overall mass) because the main-frame is the main component of the product.

The **verification procedure** is based on the provision of a declaration about the value of the Reusability index supported by technical documentation, as:

- The BOM, with the detail of the mass of the components and the disassembly report;
- A declaration that the components 'main frame' is suitable for reuse, supported by sufficient technical documentation (e.g. the design plans, the description of the necessary of the 'main frame', the description of how the 'main frame' is remanufactured for the production of new devices).
- Documentation regarding procedures and actions that the manufacturer has put into practise to collect and reuse the 'main frame' at the product's EoL.

5.3.2 Calculation of the Recyclability ratio

Before calculating the Recyclability ratio '$R_{Recycle}$' it is necessary to estimate, for each component, the values of the sub-indices:

- Disassemblability,
- Material contamination and
- Material degradation.

Disassemblability is calculated with the method of Chapter 2.5.2.3. In particular, it is assumed that the Printed Circuit Board is addressed to a shredder after a first step of manual disassembly. All the other components are manually disassembled after various steps (as described in Table 29). Manuals and packaging do not need disassembly because already separated from the product. Disassemblability is therefore calculated on the basis of the time 't' for the disassembly and the number 'n' of disassembly steps. These values have been implemented into Table 5 for the calculation of the Disassemblability index 'D'. Results are shown in Table 31.

Successively, the disassembly index of the different materials of the Printed Circuit Board is calculated. We take into consideration the separation rates of materials by the shredder, as shown in Table 6. We underline that the method supposed that only metals can be separated by shredding for the recycling; plastics can be only separated for the energy recovery.

Table 31 Calculation of the disassembly index 'D' for the manual disassembly of each component of the Hard-Disk.

Component	Disassembly code	Time *'t'* [s]	Number of disassembly steps *'n'*	**D [%]**
Printed Circuit Board	1	56	1	100%
Top Cover	2	136	2	78%
Hard Disk	3	153	3	76%
Upper circular plate	4	168	4	74%
Circular plate that holds the hard disk	5	183	5	72%
Pointer assembly	6.1	220	7	68%
Pointer Holding Frame	6.2	220	7	68%
Bottom circular Plate	7	256	8	56%
Plastic assembly	8	269	9	54%
Main Frame	9	269	9	54%
Packaging	10			100%
Manual	11			100%

The *Contamination index* for recycling is estimated from Table 11. It results that the contamination index C_1' amounts to 50% for metals of the Printed Circuit Board (due to the contamination occurring during the shredding).

Contamination concerns also the use of the labels and ink into the external framework and the external cardboard packaging.

From the BOM it results that the mass of the label into the 'external frame' is less than 1% of the component and, furthermore, we assume that the label is compatible with the recycling (easy to remove without leaving residues on the frame) [76]. No contamination occurs due to labels (C_1'=100%).

About the packaging, labels and ink are more than 1% in mass and they can depreciate the potential for recycling of the cardboard. From table 12 it results that C_1'=75%.

Content of hazardous substances (mercury and cadmium) into the Printed Circuit Board is not sufficient to contaminate the other materials. Furthermore, contamination does not occur for the ABS plastic due to flame retardant (although under study, Tetrabromobisphenol A is not considered a SVHC by the REACH Directive).

All the other components do not have sources of contamination.

The last index regards the *Material degradation* during the recycling. Values of the Material degradation index M_D are derived from Table 13.

The product's Recyclability Ratio amounts to 57.5%.

The **verification procedure** is based on the provision of a declaration about the value of the Recyclability index supported by technical documentation, as:

- The BOM, with the detail of the mass of the components and the disassembly report;
- A description of the label applied to the external framework, and a declaration that the label is easy to remove and it is compatible with the recycling of the component.

5.3.2.1 Use of alternative procedures to calculate the Disassembly index for the Recyclability Ratio

Chapter 2.5.3.4 introduces some alternative methodologies to calculate the manual disassemblability. The present paragraph applies these alternatives for the measurement of the Recyclability of the hard-disk case-study.

It is initially assumed that the Printed Circuit Board is still addressed to the shredding, while packaging and the manuals are recycled as in the previous chapter 5.3.2. Therefore their disassembly indices are the same of Table 31.

[76] This assumption has to be done by the manufacturer during the compiling of the BOM, and it has to be supported by sufficient technical documentation (as detailed in the below verification procedure).

The manual disassembly of other components is instead estimated on the basis of the 'economic value' of the component and the 'disassembly time' (Table 8). Economic values[77] of the secondary materials are: aluminium 2.02 [€/kg]; steel 0.19 [€/kg]; ABS 0.24 [€/kg].

Considering the BOM of Table 28, it is noted the low economic value of the hard-disk's components after their use; the time for disassembly is instead unvaried. From Table 8 it results that Disassembly index is always 0%: it means that, under these assumptions, the recycling cannot pay-back the costs for the manual disassembly. New values of the Disassembly index have been implemented into the Recyclability calculation spreadsheet (Table 32).

The new recyclability ratio is very low and amounts to 4.7%.

This result confirms that the use of economic parameter to estimate the disassemblability it is not recommended for products made by small components. The effect would be, in fact, to discourage the manual disassembly[78].

[77] Values of secondary materials derive from Annex I, Figure A1.1 and Table A1.1. Conversion factor: 1 euro equal to 0.75 dollars.

[78] We also recall the discussion of Deliverable 1 – Chapter 2.3.4- about the management of the EOL of small product. These are generally not separately collected but disposed by users into unsorted bins.

Table 32 Calculation of the recyclability ratio using the economic methodology to calculate the manual disassembly of each component of the Hard-Disk.

Component		Details		Economic value		Time for disassembly	Recyclability			
Name	*Disassembly code*	*Material description*	*Mass* [kg]	*v [€/kg]*	*V [€/kg]*	*t [s]*	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$
Printed Circuit Board	1	Glass	1.2E-02	-	-	-				
		Copper	1.2E-02	-	-	-	85.0%	50%	100%	5.1E-03
		Epoxy Resin	7.6E-03	-	-	-				
		Ceramics	4.2E-03	-	-	-				
		TBBP-A	3.5E-03	-	-	-				
		Iron	1.4E-03	-	-	-	95.0%	50%	100%	6.6E-04
		Aluminium	8.5E-04	-	-	-	90.0%	50%	100%	3.8E-04
		Lead	6.4E-04	-	-	-	80.0%	50%	100%	2.6E-04
		Nickel	2.4E-04	-	-	-	80.0%	50%	100%	9.6E-05
		Barium	1.8E-04	-	-	-				
		Zinc	3.0E-05	-	-	-	80.0%	50%	100%	1.2E-05
		Gold	2.0E-05	-	-	-	95.0%	50%	100%	9.5E-06
		Silver	2.0E-05	-	-	-	95.0%	50%	100%	9.5E-06
		Antimony	1.0E-05	-	-	-				
		Chromium	1.4E-06	-	-	-				
		Cadmium	1.1E-07	-	-	-				
		Beryllium	4.7E-08	-	-	-				
		Mercury	1.4E-09	-	-	-				
		Steel	4.8E-04	-	-	-	100%	100%	100%	4.8E-04
Top Cover	2	Aluminium	0.12	2.02	2.4E-01	136	0%	100%	100%	0
		Steel	1.3E-03	0.19	2.4E-04	136	0%	100%	100%	0
Hard Disk	3	Aluminium	0.022	2.02	4.4E-02	153	0%	100%	100%	0
		Steel	4.8E-04	0.19	9.1E-05	153	0%	100%	100%	0
Upper circular plate	4	Aluminium	0.01	2.02	1.2E-02	168	0%	100%	100%	0
Circular plate that holds the hard disk	5	Aluminium	0.002	2.02	4.0E-03	183	0%	100%	100%	0
		Steel	3.2E-04	0.19	6.1E-05	183	0%	100%	100%	0
Pointer assembly	6.1	Aluminium	0.01	2.02	1.6E-02	220	0%	100%	100%	0
Pointer Holding Frame	6.2	Steel	0.08	0.19	1.4E-02	220	0%	100%	100%	0
		Steel	8.0E-04	0.19	1.5E-04	220	0%	100%	100%	0
Bottom circular Plate	7	Aluminium	0.05	2.02	1.1E-01	256	0%	100%	100%	0
		Steel	4.8E-04	0.19	9.1E-05	256	0%	100%	100%	0
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	0.001	0.24	2.4E-04	269	0%	100%	84%	0
		Steel	1.6E-04	0.19	3.0E-05	269	0%	100%	100%	0
Main Frame	9	Aluminium	0.242	2.02	4.9E-01	269	0%	100%	100%	0
Packaging	10	Corrugated Cardboard	0.030	-	-	-	100%	75%	16%	3.6E-03
		PE-LD	0.001	-	-	-	100%	100%	71%	7.1E-04
		PS-E	0.020	-	-	-	100%	100%	86%	1.7E-02
Manual	11	Paper	0.010	-	-	-	100%	100%	16%	1.6E-03
		Total mass "m_{tot}" [kg]	0.64				$\Sigma\ m_{recycle}$ [kg]			0.03
							$R_{Recycle}$ [%]			**4.7%**

Another option for the disassembly is represented by the shredding of the full product without any manual disassembly (except packaging and manuals that are separated from the product). The results in this case are shown in Table 33.

Recyclability Ratio amounts in this case to 42.6%.

Note that this value is lower than that of Chapter 5.3.2, showing the need to prioritize the manual disassembly compared to the full product shredding.

Table 33 Calculation of the recyclability ratio assuming the shredding of the entire product

Component		Details			Recyclability			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass* [kg]	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$
Printed Circuit Board	1	Glass		1.2E-02				
		Copper		1.2E-02	85%	50%	100%	5.1E-03
		Epoxy Resin	Combustible-LHV: 30 MJ/kg	7.6E-03				
		Ceramics		4.2E-03				
		TBBP-A	Flame retardant Tetrabromobisphenol A (FR14)	3.5E-03				
		Iron		1.4E-03	95%	50%	100%	6.6E-04
		Aluminium		8.5E-04	90%	50%	100%	3.8E-04
		Lead		6.4E-04	80%	50%	100%	2.6E-04
		Nickel		2.4E-04	80%	50%	100%	9.6E-05
		Barium		1.8E-04				
		Zinc		3.0E-05	80%	50%	100%	1.2E-05
		Gold		2.0E-05	95%	50%	100%	9.5E-06
		Silver		2.0E-05	95%	50%	100%	9.5E-06
		Antimony		1.0E-05				
		Chromium		1.4E-06				
		Cadmium		1.1E-07				
		Beryllium		4.7E-08				
		Mercury		1.4E-09				
		Steel	Screws	4.8E-04	100%	100%	100%	4.8E-04
Top Cover	2	Aluminium	Labelled (plastic adhesive label, mass <0.1%, removable and compatible with recycling)	0.12	90%	50%	100%	5.4E-02
		Steel	Screws	1.3E-03	95%	50%	100%	6.1E-04
Hard Disk	3	Aluminium		0.022	90%	50%	100%	9.9E-03
		Steel	Screws	4.8E-04	95%	50%	100%	2.3E-04
Upper circular plate	4	Aluminium		0.01	90%	50%	100%	2.7E-03
Circular plate that holds the hard disk	5	Aluminium		0.002	90%	50%	100%	9.0E-04
		Steel	Screws	3.2E-04	95%	50%	100%	1.5E-04
Pointer assembly	6.1	Aluminium		0.01	90%	50%	100%	3.6E-03
Pointer Holding Frame	6.2	Steel		0.08	95%	50%	100%	3.6E-02
		Steel	Screws	8.0E-04	95%	50%	100%	3.8E-04
Bottom circular Plate	7	Aluminium		0.05	90%	50%	100%	2.3E-02
		Steel	Screws	4.8E-04	95%	50%	100%	2.3E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; 1% Flame ret.: Tetrabromobisphenol A (FR14)	0.001				
		Steel	Screws	1.6E-04	95%	5%	100%	7.6E-06
Main Frame	9	Aluminium		0.242	90%	50%	100%	1.1E-01
Packaging	10	Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg. Inks and label are present into the package (content higher than 1%)	0.030	100%	75%	16%	3.6E-03
		PE-LD	Antistatic plastic bag. Combustible - LHV: 42 MJ/kg; Flame ret.: 2% Red Phosphorus (FR52)	0.001	100%	100%	71%	7.1E-04
		PS-E	Expanded polystyrene. Combustible-LHV: 40 MJ/kg. Flamer retardant: 0.1% Hexabromocyclododecane HBDC (FR16)	0.020	100%	100%	86%	1.7E-02
Manual	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.010	100%	100%	16%	1.6E-03
		Total mass "m_{tot}" [kg]		0.64			$\Sigma\, m_{recycle}$ [kg]	0.27
							$R_{Recycle}$ [%]	**42.6%**

5.3.3 Calculation of the Energy Recoverability ratio and Recoverability Ratio

The Energy Recoverability ratio '$ER_{Recovery}$' regards those components that have an embodied energy potentially recoverable by incineration.

The Recovery ratio '$R_{Recovery}$' includes, instead, components that are recyclable or/and energetically recoverable.

The Recoverability indices have been calculated for the hard-disk case-study (Table 30).

First we calculate the Energy Recoverability ratio. It involves:

- the epoxy resins contained into the Printed Circuit Board and contained into the residual of the shredder. They have a disassemblability D =50% (Table 6) and a contamination index of 50% (Table 12);
- the ABS plastic assembly. It has a disassemblability D=54% (calculated analogously to Chapter5.3.2) and no contamination (C_2'= 100%, Table 12);
- the packaging and the manuals. They have a disassemblability D =100% (no disassembly occurs) and no contamination (C_2'= 100%, Table 12).

The product's Energy Recoverability Ratio amounts to 10%.

Successively the Recoverability ratio is calculated (by applying Formula 4).

The product's Recoverability Ratio amounts to 63.9%.

The **verification procedure** is based on the provision of a declaration about the value of the Energy Recoverability indices supported by technical documentation, as:

- The BOM, with the detail of the mass of the components, the disassembly report and the Lower Heating Values of the combustible materials;
- A declaration that contamination of labels and ink does not interfere with the energy recoverability of the cardboard packaging.

5.4 Calculation of the combined 'Reusability/Recyclability' and 'Reusability/Recoverability' indices for the hard disk case-study

The present chapter applies the combined 'Reusability/Recyclability' and 'Reusability/Recoverability' indices to the hard-disk case study. The calculation follows the formulas of Chapter 2.7 and the calculation spreadsheet of Table 15.

Values of the Disassemblability, Material degradation and Material contamination indices are those already calculated in Chapter 5.3.

It results that (Table 34):

- Reusability/Recyclability index amounts to 71.2%;
- Reusability/Recoverability ratio amounts to 77.5%.

The **verification procedure** is based on the provision of a declaration about the calculated values supported by technical documentation, analogously to that provided for the verification procedures of Chapters 5.3.1, 5.3.2 and 5.3.3:

Table 34 Calculation the combined Reusability/Recyclability and Reusability/Recoverability indices for the hard-disk case study

Component		Details		Reusability			Recyclability				Recoverability				Reusability-recyclability	Reusability-recoverability
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	M_D [%]	m_{reuse}	D [%]	C'_1 [%]	M_R [%]	$m_{recycle}$	D [%]	C'_2 [%]	$m_{recovery}$	($m_{recycle}$ + $m_{E\text{-}recovery}$)	$m_{reuse/recycle}$	$m_{reuse/recovery}$
Printed Circuit Board	1	Glass	1.2E-02													
		Copper	1.2E-02				85%	50%	100%	5.1E-03				5.1E-03	5.1E-03	5.1E-03
		Epoxy Resin	7.6E-03								50%	50%	1.9E-03	1.9E-03	0.0E+00	1.9E-03
		Ceramics	4.2E-03													
		TBBP-A	3.5E-03													
		Iron	1.4E-03				95%	50%	100%	6.6E-04				6.6E-04	6.6E-04	6.6E-04
		Aluminium	8.5E-04				90%	50%	100%	3.8E-04				3.8E-04	3.8E-04	3.8E-04
		Lead	6.4E-04				80%	50%	100%	2.6E-04				2.6E-04	2.6E-04	2.6E-04
		Nickel	2.4E-04				80%	50%	100%	9.6E-05				9.6E-05	9.6E-05	9.6E-05
		Barium	1.8E-04													
		Zinc	3.0E-05				80%	50%	100%	1.2E-05				1.2E-05	1.2E-05	1.2E-05
		Gold	2.0E-05				95%	50%	100%	9.5E-06				9.5E-06	9.5E-06	9.5E-06
		Silver	2.0E-05				95%	50%	100%	9.5E-06				9.5E-06	9.5E-06	9.5E-06
		Antimony	1.0E-05													
		Chromium	1.4E-06													
		Cadmium	1.1E-07													
		Beryllium	4.7E-08													
		Mercury	1.4E-09													
		Steel	4.8E-04				100%	100%	100%	4.8E-04				4.8E-04	4.8E-04	4.8E-04
Top Cover	2	Aluminium	0.12				78%	100%	100%	9.4E-02				9.4E-02	9.4E-02	9.4E-02
		Steel	1.3E-03				78%	100%	100%	1.0E-03				1.0E-03	1.0E-03	1.0E-03
Hard Disk	3	Aluminium	0.022				76%	100%	100%	1.7E-02				1.7E-02	1.7E-02	1.7E-02
		Steel	4.8E-04				76%	100%	100%	3.6E-04				3.6E-04	3.6E-04	3.6E-04
Upper circular plate	4	Aluminium	0.006				74%	100%	100%	4.4E-03				4.4E-03	4.4E-03	4.4E-03
Circular plate that holds the hard disk	5	Aluminium	0.002				72%	100%	100%	1.4E-03				1.4E-03	1.4E-03	1.4E-03
		Steel	3.2E-04				72%	100%	100%	2.3E-04				2.3E-04	2.3E-04	2.3E-04
Pointer assembly	6.1	Aluminium	0.008				68%	100%	100%	5.4E-03				5.4E-03	5.4E-03	5.4E-03
Pointer Holding Frame	6.2	Steel	0.076				68%	100%	100%	5.2E-02				5.2E-02	5.2E-02	5.2E-02
		Steel	0.001				68%	100%	100%	5.4E-04				5.4E-04	5.4E-04	5.4E-04
Bottom circular Plate	7	Aluminium	0.052				56%	100%	100%	2.9E-02				2.9E-02	2.9E-02	2.9E-02
		Steel	4.8E-04				56%	100%	100%	2.7E-04				2.7E-04	2.7E-04	2.7E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	0.001				54%	100%	84%	2.3E-04	54%	100%	5.4E-04	7.7E-04	2.3E-04	7.7E-04
		Steel	1.6E-04				54%	100%	100%	8.6E-05				8.6E-05	8.6E-05	8.6E-05
Main Frame	9	Aluminium	0.242	54%	67%	0.087	54%	100%	100%	1.3E-01				1.3E-01	2.2E-01	2.2E-01
Packaging	10	Corrugated Cardboard	0.03				100%	75%	16%	3.6E-03	100%	100%	3.0E-02	3.0E-02	3.6E-03	3.0E-02
		PE-LD	0.001				100%	100%	71%	7.1E-04	100%	100%	1.0E-03	1.0E-03	7.1E-04	1.0E-03
		PS-E	0.02				100%	100%	86%	1.7E-02	100%	100%	2.0E-02	2.0E-02	1.7E-02	2.0E-02
Manual	11	Paper	0.01				100%	100%	16%	1.6E-03	100%	100%	1.0E-02	1.0E-02	1.6E-03	1.0E-02
											Σ $m_{E\text{-recovery}}$		0.06			
											$ER_{Recovery}$		**10.0%**			
		Total mass "mtot" [kg]	0.64		Σ m_{reuse} [kg]	0.09			Σ $m_{recycle}$ [kg]	0.37	Σ $m_{recovery}$ [kg]			0.41		
					R_{Reuse} [%]	**13.7%**			**$R_{Recycle}$ [%]**	**57.5%**	**$R_{Recovery}$ [%]**			**63.8%**		
														Σ $m_{reuse/recycle, i}$ [kg]	0.45	
														$R_{Reuse/Recycle}$ [%]	**71.2%**	
														Σ $m_{reuse/recovery,i}$ [kg]		0.49
														$R_{Reuse/Recovery}$ [%]		**77.5%**

5.5 Calculation of the Recycled content of the hard-disk

The present chapter applies the methodology for the measurement of the recycled content to the case-study of the computer hard-disk.

The calculation of the index utilized the BOM of Table 28. Furthermore, data about the recycled content of each component are needed. These should be derived from production data of the manufacturer and his suppliers. However, such information has been not available in the BOM.

The application is therefore based on some hypothetical assumptions about the materials. It is assumed that the recycled content of different materials is[79]:

- Steel: 61%;
- Aluminium: 48%;
- Lead: 77%;
- Copper: 31.5%;
- Nickel: 43%;
- Zinc: 30%;
- Chromium: 34%.

It is instead assumed that the following materials used in the hard disk do not have a recycled content:

- glass reinforced plastic (epoxy resins with glass fibres and flame retardant),
- ABS plastic,
- small components of the Printed Circuit Board (precious metals, cadmium, barium, beryllium, mercury).

Concerning the packaging it is assumed that the cardboard has a recycled content of 30%, while the manuals are produced from 100% recycled fibres.

Average recycled contents of materials have been then implemented into the calculation spreadsheets. Results are shown in Table 35 and 36.

Note that the recycled content of the hard-disk has been separated from the recycled content of the ancillary components (packaging and manuals) in order to show their different contribution.

The recycled content of the overall product is the weighed sum of the two contributions. It results that:

- The recycled content of the hard disk amounts to 47.2%:
- The recycled content of the packaging disk amounts to 31.1%.

[79] Data about recycled content of metals refer to average data in 2008 in USA (from [USGS, 2010b])

Table 35 Case-study calculation of the Recycled content of the hard-disk

Component		Details			Recycled content '$R_{Content}$'			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	Has the material a recycled content? [YES/NO]	Is the material self-manufactured? [YES/NO]	Material recycled content '$r_{Content}$' [%]	'$r_{Content}$' * m_i [kg]
Printed Circuit Board	1	Glass		1.2E-02	not available			
		Copper		1.2E-02	YES	NO	31.5%	3.7E-03
		Epoxy Resin	Combustible-LHV: 30 MJ/kg	7.6E-03	not available			
		Ceramics		4.2E-03	not available			
		TBBP-A	Flame retardant Tetrabromobisphenol A (FR14)	3.5E-03	not available			
		Iron		1.4E-03	YES	NO	61%	8.4E-04
		Aluminium		8.5E-04	YES	NO	48%	4.1E-04
		Lead		6.4E-04	YES	NO	77%	4.9E-04
		Nickel		2.4E-04	YES	NO	43%	1.0E-04
		Barium		1.8E-04	not available			
		Zinc		3.0E-05	YES	NO	30%	9.0E-06
		Gold		2.0E-05	not available			
		Silver		2.0E-05	not available			
		Antimony		1.0E-05	not available			
		Chromium		1.4E-06	YES	NO	34%	4.8E-07
		Cadmium		1.1E-07	not available			
		Beryllium		4.7E-08	not available			
		Mercury		1.4E-09	not available			
		Steel	Screws	4.8E-04	YES	NO	61%	2.9E-04
Top Cover	2	Aluminium	Labelled (plastic adhesive label, mass <0.1%, removable and compatible with recycling)	0.12	YES	NO	48%	5.8E-02
		Steel	Screws	1.3E-03	YES	NO	61%	7.8E-04
Hard Disk	3	Aluminium		0.022	YES	NO	48%	1.1E-02
		Steel	Screws	4.8E-04	YES	NO	61%	2.9E-04
Upper circular plate	4	Aluminium		0.01	YES	NO	48%	2.9E-03
Circular plate that holds the hard disk	5	Aluminium		0.002	YES	NO	48%	9.6E-04
		Steel	Screws	3.2E-04	YES	NO	61%	2.0E-04
Pointer assembly	6.1	Aluminium		0.01	YES	NO	48%	3.8E-03
Pointer Holding Frame	6.2	Steel		0.08	YES	NO	61%	4.6E-02
		Steel	Screws	8.0E-04	YES	NO	61%	4.9E-04
Bottom circular Plate	7	Aluminium		0.05	YES	NO	48%	2.5E-02
		Steel	Screws	4.8E-04	YES	NO	61%	2.9E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	Combustible-LHV: 38 MJ/kg; 1% Flame ret.: Tetrabromobisphenol A (FR14)	0.001	not available			
		Steel	Screws	1.6E-04	YES	NO	61%	9.8E-05
Main Frame	9	Aluminium		0.242	YES	NO	48%	0.11616
							Σ ($r_{content}$ * m_i) [kg]	0.271
			Total mass "m_{tot}" [kg]	**0.576**			***$R_{Content}$* [%]**	**47.2%**

The **verification procedure** of the recycled content is based on a self-declaration of the manufacturer supported by technical documentation e.g.material flows declaration or chain of custody declaration from manufacturer and its suppliers.

Table 36 Case-study: calculation the Recycled content of the hard-disk packaging

Component		Details			Recycled content '$R_{Content}$'			
Name	*Disassembly code*	*Material description*	*Content details*	*Mass [kg]*	Has the material a recycled content? [YES/NO]	Is the material self-manufactured? [YES/NO]	Material recycled content '$r_{Content}$' [%]	'$r_{Content}$' * m_i [kg]
Packaging	10	Corrugated Cardboard	Combustible-LHV: 16.9 MJ/kg. Inks and label are present into the package (content higher than 1%)	0.030	YES	NO	30%	9.0E-03
		PE-LD	Antistatic plastic bag. Combustible-LHV: 16.9 MJ/kg. Combustible - LHV: 42 MJ/kg; Flame ret.: 2% Red Phosphorus (FR52)	0.001	not available			
		PS-E	Expanded polystyrene. Combustible-LHV: 40 MJ/kg. Flamer retardant: 0.1% Hexabromocyclododecane HBDC (FR16)	0.020	not available			
Manual	11	Paper	Combustible-LHV: 18.4 MJ/kg	0.010	YES	NO	100%	1.0E-02
							Σ ($r_{content}$ * m_i) [kg]	0.019
			Total mass "m_{tot}" [kg]	**0.1**			***R*** ***Content*** **[%]**	**31.1%**

5.6 Calculation of the 'RRR Benefit Ratio' indices for the hard disk case-study

The present chapter describes the application of the RRR Benefit Ratio indices (introduced in Chapter 3.5) to the hard-disk case-study.

Values of the disassemblability, material degradation and contamination index are those already calculated in Table 32.

The estimated environmental benefits, in term of saved CO_{2eq}, are shown in Tables 37, 38 and 39. It is estimated that:

- the Reusability Benefit Ratio amounts to 33.4%. The potential benefits related to the reuse of product's components amount to 1.76 kg CO2eq.;
- the Recyclability Benefit Ratio amounts to 61.3%. The potential benefits related to the recycle of product's components amount to 3 kg CO2eq;
- the Energy Recoverability Benefit Ratio amounts to 89.5%. The potential benefits related to the energy recovery of product's components amount to 0.08 kg CO2eq.

It is observed that the potential benefits related to the Reusability are lower than those related to the Recyclability. This happens because only one component ('main frame') of the product is reusable, while the majority of the components are recyclable.

Note that a reusable components could be further recycled, adding the benefits related to the reuse to those related to the recycling. It is, instead, not true the 'vice-versa': components recycled cannot be successively reused.

It is also possible to compare the results of the present chapter with those of Chapter 5.3. It is observed that the indices for Reusability and Recyclability have small variation. This is related to the peculiarities of the selected case study, where components with the highest mass are also those responsible of the highest environmental impacts.

It is instead observed a large difference among the results of Recoverability index of Chapter 5.3 and the Energy Recoverability Benefit index of the present chapter. The reason is this last index is applied only to those components that have an 'energy content' potentially recoverable. The previous Recoverability index, instead, represented the fraction of recoverable materials divided the full product's mass. The different assumption for the calculation of the two indices causes very different results.

A particular interesting result is represented by the content of gold into the printed circuit board. Mass fraction of gold is, in fact, negligible. On the other side, gold has very high environmental burdens related to its production and it has also a very high value of the differential impact index[80]. Consequently the contribution of the gold is negligible in the indices based on the mass fraction; instead the recycling of the gold contributes significantly (about 7%) to the Reusability/Recyclability Benefits index.

The case-study showed that the modified indices, based on the resource prioritisation and the potential environmental benefits of RRR, are more representative than the simple mass indices. The 'RRR Benefit Ratio' indices, in fact, take into account the potential benefits that could be achieved by reuse/recycle/recovery the product's components.

The **verification procedure** is based on self-declarations of the manufacturer supported by technical documentation available before the product is put into the market and provided on request.

Declarations could be verified e.g. by a Market Surveillance Authority (MSA) that can check the truthfulness of provided information (e.g. BOM, disassembly scheme and disassembly report) and successively would follow the calculation done by the manufacturer in specific 'calculation data sheet'

In particular the authority should check the correctness and representativeness of employed data about:

- Heating values of materials;
- Differential impact indices of materials;
- Impacts related to primary materials production.

[80] Differential impact index of gold: 18,431 $kg_{CO2eq.}$ (data from [ecoinvent 2.0]).

Table 37 Case-study: calculation of the Reusability Benefit Ratio

Component		Details		Disassemblability	Material Degradation	Impact for primary production	Potential benefits related to reuse
Name	*Disassembly code*	*Material description*	*Mass [kg]*	D [%]	M_D [%]	I_{GWP} [$kgCO_{2eq.}$/kg]	[$kgCO_{2eq.}$]
Printed Circuit Board	1	Glass	1.2E-02			0.77	
		Copper	1.2E-02			3.20	
		Epoxy Resin (*)	7.6E-03			6.73	
		Ceramics (*)	4.2E-03			0.84	
		TBBP-A	3.5E-03			n.a.	
		Iron	1.4E-03			2.98	
		Aluminium	8.5E-04			9.67	
		Lead	6.4E-04			1.78	
		Nickel	2.4E-04			24.80	
		Barium	1.8E-04			n.a.	
		Zinc	3.0E-05			3.17	
		Gold (*)	2.0E-05			19,281	
		Silver (*)	2.0E-05			103.11	
		Antimony	1.0E-05			n.a.	
		Chromium	1.4E-06			n.a.	
		Cadmium (*)	1.1E-07			0.87	
		Beryllium	4.7E-08			n.a.	
		Mercury (*)	1.4E-09			118.06	
		Steel	4.8E-04			2.98	
Top Cover	2	Aluminium	0.12			9.67	
		Steel	1.3E-03			2.98	
Hard Disk	3	Aluminium	0.022			9.67	
		Steel	4.8E-04			2.98	
Upper circular plate	4	Aluminium	0.006			9.67	
Circular plate that holds the hard disk	5	Aluminium	0.002			9.67	
		Steel	3.2E-04			2.98	
Pointer assembly	6.1	Aluminium	0.008			9.67	
Pointer Holding Frame	6.2	Steel	0.076			2.98	
		Steel	0.001			2.98	
Bottom circular Plate	7	Aluminium	0.052			9.67	
		Steel	4.8E-04			2.98	
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS) (**)	0.001			3.87	
		Steel	1.6E-04			2.98	
Main Frame	9	Aluminium	0.242	100%	75%	9.67	1.76
Packaging	10	Corrugated Cardboard	0.03			0.68	
		PE-LD	0.001			2.10	
		PS-E	0.02			4.49	
Manual	11	Paper	0.01			0.97	
				$Reuse_{Benefit}$ [$kgCO_{2eq.}$]			1.76
				$Reuse_{Benefit,Max}$ [$kgCO_{2eq.}$]			5.24
				Reusability Benefit Ratio "$Reusability_{Benefit}$" [%]			33.47%

Table 38 Case-study: calculation of the Recyclability Benefit Ratio

Component: *Name*	Component: *Disassembly code*	Details: *Material description*	Details: *Mass [kg]*	Disassemblability D [%]	Contamination Index C'_1 [%]	Material Degradation M_R [%]	Differential impact δ_{GWP} [$kgCO_{2eq.}$/kg]	Potential benefits related to recycling [$kgCO_{2eq.}$]
Printed Circuit Board	1	Glass	1.2E-02				0.77	
		Copper	1.2E-02	85.0%	50%	100%	2.76	1.4E-02
		Epoxy Resin	7.6E-03				n.a.	
		Ceramics	4.2E-03				n.a.	
		TBBP-A	3.5E-03				n.a.	
		Iron	1.4E-03	95.0%	50%	100%	2.16	1.4E-03
		Aluminium	8.5E-04	90.0%	50%	100%	9.17	3.5E-03
		Lead	6.4E-04	80.0%	50%	100%	1.25	3.2E-04
		Nickel	2.4E-04	80.0%	50%	100%	n.a.	
		Barium	1.8E-04					
		Zinc	3.0E-05	80.0%	50%	100%	2.69	3.2E-05
		Gold (*)	2.0E-05	95.0%	50%	100%	18,431	1.8E-01
		Silver (*)	2.0E-05	95.0%	50%	100%	88.55	8.4E-04
		Antimony	1.0E-05				n.a.	
		Chromium	1.4E-06				n.a.	
		Cadmium	1.1E-07				n.a.	
		Beryllium	4.7E-08				n.a.	
		Mercury	1.4E-09				n.a.	
		Steel	4.8E-04	100%	100%	100%	2.16	1.0E-03
Top Cover	2	Aluminium	0.12	78%	100%	100%	9.17	8.6E-01
		Steel	1.3E-03	78%	100%	100%	2.16	2.2E-03
Hard Disk	3	Aluminium	0.022	76%	100%	100%	9.17	1.5E-01
		Steel	4.8E-04	76%	100%	100%	2.16	7.9E-04
Upper circular plate	4	Aluminium	0.006	74%	100%	100%	9.17	4.1E-02
Circular plate that holds the hard disk	5	Aluminium	0.002	72%	100%	100%	9.17	1.3E-02
		Steel	3.2E-04	72%	100%	100%	2.16	5.0E-04
Pointer assembly	6.1	Aluminium	0.008	68%	100%	100%	9.17	5.0E-02
Pointer Holding Frame	6.2	Steel	0.076	68%	100%	100%	2.16	1.1E-01
		Steel	0.001	68%	100%	100%	2.16	1.2E-03
Bottom circular Plate	7	Aluminium	0.052	56%	100%	100%	9.17	2.7E-01
		Steel	4.8E-04	56%	100%	100%	2.16	5.8E-04
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS) (**)	0.001	54%	50%	84%	2.44	5.5E-04
		Steel	1.6E-04	54%	100%	100%	2.16	1.9E-04
Main Frame	9	Aluminium	0.242	54%	100%	100%	9.17	1.2E+00
Packaging	10	Corrugated Cardboard	0.03	100%	75%	16%	0.12	4.3E-04
		PE-LD	0.001	100%	100%	71%	1.2	8.5E-04
		PS-E	0.02	100%	100%	86%	3.5	6.1E-02
Manual	11	Paper	0.01	100%	100%	16%	0.46	7.4E-04
				$Recycle_{Benefit}$ [$kgCO_{2eq.}$]				3.0
				$Recycle_{Benetit,Max}$ [$kgCO_{2eq.}$]				4.8
				Recyclability Benefit Ratio '$Recyclability_{,Benefit}$' [%]				61.3%

(*) differential impact data from [Ecoinvent 2.0]

(**) Differential impacts of ABS is not available. It is asumed that it is equal to that of PET

Table 39 Case-study: calculation of the Energy Recoverability Ratio

Component: *Name*	Component: *Disassembly code*	Details: *Material description*	Details: *Mass [kg]*	Disassemblability D [%]	Contamination Index C'2 [%]	Lower Heating Value [MJ/kg]	Potential recoverable energy [MJ]
Printed Circuit Board	1	Glass	1.2E-02				
		Copper	1.2E-02				
		Epoxy Resin	7.6E-03	50.0%	50%	30	0.06
		Ceramics	4.2E-03				
		TBBP-A	3.5E-03				
		Iron	1.4E-03				
		Aluminium	8.5E-04				
		Lead	6.4E-04				
		Nickel	2.4E-04				
		Barium	1.8E-04				
		Zinc	3.0E-05				
		Gold	2.0E-05				
		Silver	2.0E-05				
		Antimony	1.0E-05				
		Chromium	1.4E-06				
		Cadmium	1.1E-07				
		Beryllium	4.7E-08				
		Mercury	1.4E-09				
		Steel	4.8E-04				
Top Cover	2	Aluminium	0.12				
		Steel	1.3E-03				
Hard Disk	3	Aluminium	0.022				
		Steel	4.8E-04				
Upper circular plate	4	Aluminium	0.006				
Circular plate that holds the hard disk	5	Aluminium	0.002				
		Steel	3.2E-04				
Pointer assembly	6.1	Aluminium	0.008				
Pointer Holding Frame	6.2	Steel	0.076				
		Steel	0.001				
Bottom circular Plate	7	Aluminium	0.052				
		Steel	4.8E-04				
Plastic assembly	8	Acrylonitrile butadiene styrene (ABS)	0.001	54%	100%	38	0.02
		Steel	1.6E-04				
Main Frame	9	Aluminium	0.242				
Packaging	10	Corrugated Cardboard	0.03	100%	100%	16.9	0.51
		PE-LD	0.001	100%	100%	42	0.04
		PS-E	0.02	100%	100%	40	0.80
Manual	11	Paper	0.01	100%	100%	18.4	0.18

Energy conversion factor 'η'	0.3
Specific Environmental benefit [kg $CO_{2eq.}$/kWh]	0.59
Potential recoverable energy "$ER_{Potential}$"[MJ]	0.48
"$ER_{Benefit}$" [kg $CO_{2.eq.}$]	0.08
"$ER_{Benefit,Max}$" [kg $CO_{2.eq.}$]	0.09
Energy Recoverability Benefit Ratio "$ERecoverability_{Benefit}$" [%]	89.5%

5.7 Conclusions and recommendations

The previous chapters illustrate the application of the proposed set indices to a case-study product. The main outcomes of the analysis are:

- the 'key' role of the BOM. A detailed and clear BOM is the first step for all the next calculations;
- The Reusability/Recyclability/Recoverability Benefit Indices (introduced in Chapter 3.5) are preferable to the simple RRR indices (introduced in Chapter 2). This is due to the implementation of life-cycle data in the calculation procedure. The new indices are, therefore, more representative than the simple mass indices because they relate to the effective burdens due to the production and recycling of the materials. The use of these new indices could address designers into identifying those components whose reuse/recycle/recovery can grant the highest environmental benefits (e.g. gold and other precious metals contained into printed circuit board, otherwise not relevant in terms of mass fraction of the product).
- However, it is important to highlight that the requirements setting minimum thresholds for the 'RRR indices' or the 'RRR Benefit Ratio' indices could potentially lead to design measures that worsen the product's overall environmental life cycle performance. A life-cycle check and a case-by-case analysis is necessary to avoid potential shifting of burdens (for more details, see also Chapter 7.4)
- Requirements concerning the 'post-consumer' recycled content should be set for specific material, including:
    - Priority materials (as e.g. those identified by the EU study on "critical raw material");
    - Materials responsible of the highest environmental impacts during their life-cycle;
    - Materials whose recycling needs to be fostered (e.g. materials that have a low value after the recycling).
- The use of apposite calculation spreadsheets can simplify the calculation procedure and also the verification process;
- The verification process should be based on self-declarations of the manufacturer supported by technical documentation available before the product is put into the market and provided on request (e.g. a check by the competent body). The check should focus on:
    - The truthfulness of information presented in the BOM, the disassembly scheme and the disassembly report;
    - The calculation done by the manufacturer in the 'calculation data sheet'.

5.8 Summary

The present Chapter applies the previously introduced methodologies for the measurement and verification of the *RRR*, the recycled content and the resources prioritisation to a case-study product: a computer's hard disk. Data about the product have been derived from an exemplary product described in the scientific literature.

First, the BOM and the product's disassembly scheme have been introduced. Successively, Reusability/Recyclability/Recoverability indices have been calculated.

Concerning the recycled content, data from suppliers were not available. The index has been therefore calculated on the basis of average values of recycled content of materials from the literature.

The last part of the case study concerns the calculation of the Reuse/Recycle/Recovery Benefit Indices to the product and the identification of components that can contribute more to the potential environmental benefits.

The results of the case study analysis represent the basis for the elaboration of potential requirements for the Ecodesign of the product. This topic will be illustrated in the following chapter.

6 Assessment at the design stage of use of hazardous substances into products

6.1 Introduction

The European Directive 2002/95/EC [EU, 2002] aims at fixing Restriction of Hazardous Substances (RoHS) in electrical and electronic equipments. The list of restricted substances includes: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) [81].

Concerning the identification of new hazardous substances to be potentially regulated, Deliverable 1[82] underlined the key contribution of the REACH Regulation [EU, 2006]. In particular, the regulation fixes the criteria and the procedures for the identification of "Substances of Very High Concern" (SVHC), meaning the substances that, according to the precaution principle, need to be carefully evaluated and further investigated/studied. "*Substances meeting the criteria for classification as substances of very high concern (SVHC) in accordance with REACH could be used to identify additional hazardous substances to be regulated under the RoHs*" [EC, 2008b].

The scope of the present chapter is the assessment of the use of hazardous substances into EUP. In particular, the chapter describes a multi-criteria life-cycle approach to assess how the content of hazardous substances can affect the ecoprofile of a case-study product.

This methodology can be useful to identify some key components of the product that have higher environmental impacts. These components could be therefore the focus of some potential requirements that aims at reduce the impacts of products at the design stage.

It is here highlighted that potential Ecodesign requirements concerning the restriction of the use of hazardous substances could potentially lead to design measures that worsen the product's overall environmental life cycle performance. Therefore, the definition of Ecodesign requirements that limit the use of some hazardous substances has to be assessed following the life cycle approach. The analysis should also include the assessment of all the functions of the substance in the product as, for example, the reduction of fire risks due to the use of flame retardants.

[81] For further detail on the ROHS Directive, see the Deliverable 1- Chapter 1.2.
[82] See Deliverable 1 – Chapter 1.3.

6.2 Assessment of the use of hazardous substances

The analysis of hazardous substances has to be related to the product's peculiarities. For example, *the adoption of a specific technology imposes sometimes the inclusion of some hazardous materials that are not replaceable at the current level of technology*, or their replacement could have other, even more harmful, effects (e.g. lower overall environmental performance, higher energy consumption during the use stage, etc.).

On such purposes, various exemptions to the RoHS restrictions have been developed[83]. Exemptions fix a tolerated content of hazardous substances for specific technologies/products. Exemptions can be introduced "*if substitution is not possible from the scientific and technical point of view or if the negative environmental or health impacts caused by substitution are likely to outweigh the human and environmental benefits of the substitution*" [EU, 2002]. The list of exemptions have to be periodically checked and reviewed in order to grant the consistency and adaptation of the Directive to the scientific and technical progress.

As described in Deliverable 1[84], the exempted hazardous substances are generally necessary for the correct operation of the considered technology. For example, the RoHS introduced the exemption for television about the "*use of mercury in florescent lamps in LCDs*". Mercury is mostly present into LCD technologies, as for example into *Cold Cathode Fluorescent Lamp (CCFL)* [Fraunhofer IZM, 2007]. Here the tube is phosphor coated and filled with inert gases (Ar/Ne) and a slight amount of mercury (approx. 4 mg Hg per lamp) that is essential for the operation of the component.

The technology evolution focused on the development of mercury-free lamps. Flat Florescent Lamp (FFL) is an example of a backlight 'mercury free' technology that has already entered the market. However this technology is characterized by some critical issues as "*higher power consumption in comparison to 'Cold Cathode Fluorescent Lamp'* [Fraunhofer IZM, 2007].

It can be concluded that the assessment of the use of a hazardous substance has therefore to be related to the specific product category and the specific adopted technology. The potential restriction of a substance, for example by introducing some specific requirements, has to be technologically feasible. On such purpose it is also necessary to identify and assess also the potential alternative technologies.

The comparison of products belonging to different technologies should be based on a life-cycle approach, evaluating all the impacts that occur during each life-cycle stage of the product, from the manufacture to the use and the disposal.

In fact, it is underlined that higher energy consumptions during the use phase cause higher environmental impacts (related i.e. to the impacts of the electricity production), including the emission of hazardous substances. For example Table 40 shows some emissions of hazardous substances related to the average production of 1 kWh of electricity in the EU27 [ELCD, 2010].

[83] For a complete list of exemptions, see Deliverable 1 – Chapter 1.2.
[84] Deliverable 1 – Chapter 5.4

Table 40 Emission related to the production of 1 kWh of electricity (EU-27 mix)[85]

Emitted Substance	Amount [kg/kWh]
Lead (to air)	9.85E-08
Lead (to soil)	1.95E-12
Lead (to fresh water)	1.71E-07
Lead (to sea water)	2.02E-09
Mercury (to air)	1.37E-08
Mercury (to soil)	1.12E-13
Mercury (to fresh water)	5.76E-10
Mercury (to sea water)	3.21E-11
Cadmium (to air)	3.52E-09
Cadmium (to soil)	2.50E-11
Cadmium (to fresh water)	4.03E-09
Cadmium (to sea water)	1.98E-08
Chromium VI	1.49E-17

The following paragraph will illustrate a methodological procedure to assess the use of a hazardous substance into a case-study product.

6.2.1 A methodology for the assessment of the use of hazardous substances

The present chapter presents a methodological approach for the assessment of the use of a hazardous substance into a case-study product. The approach is based on (see Figure 16):

- **STEP 1. Identification of the base-case**. It is necessary to identify/characterize the product that has to be investigated and the hazardous substance that has to be assessed. The product group has therefore to be analyzed in order to define a 'base-case' that is representative of the product/technology.
- **STEP 2. Alternatives**. Successively, an alternative product/s is/are selected. This alternative should not contain the investigated substance (or it should contain on a lower threshold than those of the base-case).
- **STEP 3. Life Cycle Assessment (LCA).** The LCA of the base-case and the alternate/s products is performed, and life-cycle inventories are calculated. In order to grant comparability of the results, LCA should be compliant with the "International Reference Life Cycle Data System (ILCD) Handbook" [ILCD, 2010]. During the Life Cycle Impact Assessment (LCIA) phase, a set of impact categories are selected for the comparison. The list of the selected environmental impacts categories is shown in Table 41[86]. It is recommended for the analysis the use of a multi-criteria approach with the selection of a large set of different impact categories.[87,88] Concerning the impact assessment phase, the normalisation and weighting represents two optional phases [ISO 14040, 2006]. These phases will not be considered in the current analysis.

[85] Data refer to the module "Electricity Mix AC; consumption mix, at consumer; < 1kV" of the European Reference Life Cycle Database (ELCD) [ELCD, 2010].
[86] In the present study the selected impact categories refer to the [CML, 2001] with characterisation factor updated to November 2009.
[87] Note that this list is not exhaustive and it could be extended by including other impact categories potential relevant
[88] For example, the methodology does not consider potentially relevant impact like.

- **STEP 4. Comparison**. The case-study products are finally compared on the basis of the different impact categories, following a multi-criteria analysis.
-

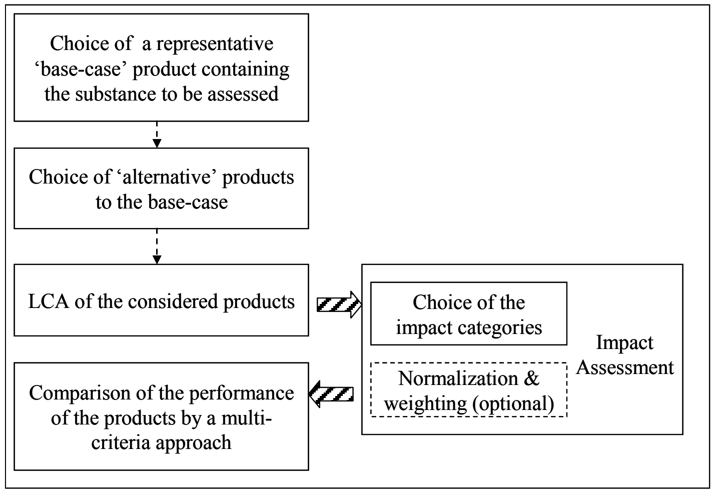


Figure 16 Methodology for the assessment of the use of hazardous substances

Table 41 List of the selected impact categories 'I' for the LCIA

Impact category	Characterization factor	Unit of measure
Resource depletion	Abiotic Depletion Potential -ADP (elements)	kg $Sb_{eq.}$
Resource depletion	Abiotic Depletion Potential – ADP (fossil fuels)	MJ
Acidification	Acidification potential - AP	kg $SO2_{eq.}$
Eutrophication	Eutrophication Potential - EP	kg $Phosphate_{eq.}$
Freshwater Aquatic Ecotoxicity	Freshwater Aquatic Ecotoxicity Pot. - FAETP	kg $DCB_{eq.}$
Climate change	Global warming Potential - GWP	kg $CO2_{eq.}$
Human Toxicity Potential	Human Toxicity Potential - HTP	kg $DCB_{eq.}$
Ozone depletion	Ozone Layer Depletion Potential - ODP	kg $R11_{eq.}$
Photochemical Ozone Creation	Photochemical Ozone Creation Potential - POCP	kg $Ethene_{eq.}$
Terrestric ecotoxicity	Terrestric ecotoxicity potential - TETP	kg $DCB_{eq.}$

The life-cycle impact data can support decision makers to compare different products/technologies on a life-cycle perspective. Furthermore, the proposed methodology can be useful to identify some key components of the product that have higher environmental impacts. These components could be therefore the focus of some potential requirements that aims at reduce the impacts of products at the design stage.

The next paragraphs will discuss the application of the methodology to the assessment of the use of a substance regulated by the RoHS Directive. The scope of the analysis is to points out how the different use/release of the hazardous substance during the life-cycle modifies the ecoprofile of the case-study products.

Note that, the proposed methodology is not related to a specific substance (as those regulated by the RoHS) but is fully applicable to the assessment of the use of SVHC (as regulated by the REACH) and also to other hazardous substances that are currently not regulated[89].

6.3 Application of the Assessment methodology to a case-study product

The scope of this paragraph is to show an exemplary and illustrative application of the proposed methodology to a case-study product. In particular, it will assess the use of mercury into Compact Fluorescent Lamps (CFL). The maximum quantity of mercury tolerated in a CFL is regulated by a RoHS exemption [EC, 2010c]:

> *Mercury in single capped (compact) fluorescent lamps not exceeding (per burners for general lighting purposes < 30 W):*
>
> - *5 mg (Expires on 31 December 2011);*
> - *3,5 mg may be used per burner after 31 December 2011 until 31 December 2012;*
> - *2,5 mg shall be used per burner after 31 December 2012.*

6.3.1 STEP 1: Identification of the base-case

Compact Fluorescent Lamps (CFL) are a typology of small fluorescent lamp. They use electricity to excite metal vapours and produce electricity. Mercury is an essential element for the operation of CFLs and is inserted during the production phase. In normal circumstances, mercury stays within the lamp enclosure during its entire lifetime and can be recycled at end-of-life. Mercury content in CFL is independent on lamp power but differences can be made between technologies (e.g. amalgam with Hg-Pb or only Hg) [Van Tichelen et al., 2009].

Thank to their small dimensions and their high energy efficiency and long lifetime, CFLs are nowadays adopted all over the world. Their diffusion is expected to grow in the next decades, and their use is also promoted by the EU and manufacturers [JRC, 2009].

Mercury use into products has been regulated by the RoHS. Due to the importance of CFL in the European energy policies, a specific exemption has been introduced for this product category. The use of mercury has been restricted to 5 mg per CFL (until December 2011).

However, nowadays other "mercury-free" technologies are available for domestic lightings (as, for example, the halogen lamps). Besides, several companies declared to manufacture CFLs with lower mercury content than the exemption threshold; some companies also produce lamps with a content of 1.1 mg per device [Van Tichelen et al., 2009].

Some innovative 'mercury-free" technologies (e.g. the Light Emitting Diode - LED lamps) are also under development and they can represent a valid alternative to CFL in the next future.

[89] For example substances that have been classified with some of the risk phrases of the Council Directive 67/548/EEC.

The following section will illustrate the application of the LCA methodology for the assessment of the use of mercury into CFL, in comparison with other alternative products.

6.3.2 STEP 2: Alternatives

The CFL is considered as the base-case of the analysis. The selected “mercury-free” products that are alternative to CFL, are:

- **halogen lamps** are a special type of incandescent lamps, with a tungsten filament and a glass envelope where the filling gas contains halogen gases. Compared to normal incandescent lamps, halogen lamps have a higher efficiency and lifetime thanks to the re-deposition cycle of the tungsten into the filament. Halogen lamps also grant a high quality light (as ‘colour temperature’ and ‘colour rendering’ indices). First halogen lamps came on the market in the years 1960. It was introduced for its increased lifetime and efficacy. The smaller size low voltage halogen lamps, introduced in the years 1970, are nowadays largely diffused in the market, representing about 30% of the current lighting devices sold in the EU [Van Tichelen et al., 2009];
- **Light Emitting Diode (LED)** is a semiconductor light source, largely used in the past decades in the electronics equipments. LED are recently becoming available on the market with increasing efficacy and increasing life time as a result of decades of semiconductor research and progress [Van Tichelen et al., 2009. LEDs that are nowadays on the market are mainly Solid State Lighting (SSL) devices, which rely on semiconductor material. Efficiency and life time of SSL devices rapidly decrease with ambient temperature, therefore no high power densities or compact light sources can be obtained. Particularly promising for the future are the OLED (Organic LED) devices. These are flat displays, made by a series of organic thin films between two conductors. When electrical current is applied, a bright light is emitted [Van Tichelen et al., 2009]. OLED’s could tackle in the future the material and cost problem currently encountered in LED.

For the next steps of the analysis, the BOM of the identified products is necessary. As discussed in Chapter 1, the needed level of detail is lower compared to the assessment of RRR potentials[90]. Unfortunately, no direct data from manufacturers were available. Therefore data for BOM have been estimated from reference data (Table 42).

The selected case-studies lamps are:

A. CFL with integrated ballast (base-case study). Data about the BOM and the technical parameters are referred to *Van Tichelen et al., 2009*[91]. Plastic housing is assumed of Acrylonitrile butadiene styrene (ABS). Mercury content was fixed to 5 mg (as the limit of the exemption threshold);

[90] In the current analysis it is not necessary to have the disassembly scheme of the products. The BOM can be restricted to the list of the utilized materials and their mass. Particular attention should be instead focused on the accounting of hazard substances that could modify significantly the Impact Assessment phase.

[91] Compact fluorescent lamp, enveloped form, E14/B15d.

B. Halogen lamp low voltage. Technical specifications and BOM refer to *Van Tichelen et al., 2009*[92]*;*

C. Globular lamp with LED[93]. The BOM has been assumed from reference [Hendrickson et al., 2010]. Technical details and performances of the lamp are derived from manufacturer's catalogues;

D. CFL with low mercury content. This case-study is similar to the base case study, except for the mercury content that it is supposed to accomplish to the new threshold (2.5 per CFL burner) starting in 2013 [EC, 2010c]. Technical specifications have been derived from a manufacturer catalogue. Compared to the base case-study, this lamp:

- Have the same BOM[94] with the only difference of the mercury content;
- Have slightly higher values of the power consumption and the luminous flux.

Data about the packaging have been estimated from manufacturer's catalogues.

[92] Halogen lamp, 12V, GY6, 35. Content of tungsten is estimated from [Garret and Collins, 2009]. Filling halogen gas is considered negligible.

[93] An interesting LCA have been recently carried out on such innovative technology [OSRAM, 2009]. Unfortunately the study does not provide detailed information about the lamp composition and disaggregated data about the manufacturing process.

[94] The lamp has technical specifications and structure very similar to the base case. It is therefore plausible to suppose for both the devices an analogous BOM.

Table 42 BOM for the studied lamps

	CFL with integrated ballast 	Halogen lamp 12 V 	LED 	CFL with low mercury content 
Power [W]	10	35	8	11
Luminous flux [lm]	400	539	345	540
Life time [h]	6000	3000	24000	6000
Color Rendering Index (CRI)	100	100	80	>80
Bill of Material (BOM)				
Material / components	Mass [g]			
Tubular + envelope (glass bulb)	35.5	2	10.7	35.5
Electronics (PCB and various circuits)	16		10.1	16
Plastic housing [a]	11		10.8	11
Caps /heat sinks (aluminium)	1		36.9	1
Filament (Tungsten)		0.5		
Filler (Mercury)	0.005			0.0023
LED			1.5	
Base (steel)			12.2	
Connector (copper)			0.5	
Packaging (Cardboard)	294	12	304	381.4

a) assumed: Acrylonitrile butadiene styrene (ABS) for CFLs: Polycarbonate for LED

6.3.3 STEP 3: Life Cycle Assessment (LCA)

The next step of the analysis is represented by the Life Cycle Assessment of the base-case study and the selected alternatives.

Due to the data shortage it was not possible a detailed analysis of all the manufacturing process. The analysis was therefore based on estimations and on data from reference. On such purpose we underline that the main scope of the case study is to show the application of the proposed methodology. A complete assessment of the selected case-study product requires more detailed data directly from manufacturers.

Concerning the technical terminology and the methodological issues of LCA, we refer to the ILCD - Handbook [EC, 2010].

The scope of the present LCA is to assess how the content of mercury influences the ecoprofile of the CFL, and to compare the case-study CFL with other alternative mercury-free lamps.

The selected Functional Unit (FU) of the study is: *an illuminating device that grants 400 lumens for 24,000 hours*[95].

It is important therefore to assess how many lamps are necessary for the fixed FU. First of all, it is considered that lamps have not a constant luminous flux over the time. The decay of performance is represented by the Lumen Maintenance Factor (LMF)[96]. In particular it is assumed that:

- Halogen lamps provide after 3000 hours 95% of the initial luminous flux[97] ;
- CFLs provide after 6000 hours 89% of the initial luminous flux[98];
- LED lamps provide after 24,000 hours 80% of the initial luminous flux[99].

Figure 17 shows the trend of the LMF of the lamps over the time. The average values of LMF are therefore:

- *CFLs = 94.5%*;
- *Halogen = 97.5%*;
- *LED = 90%.*

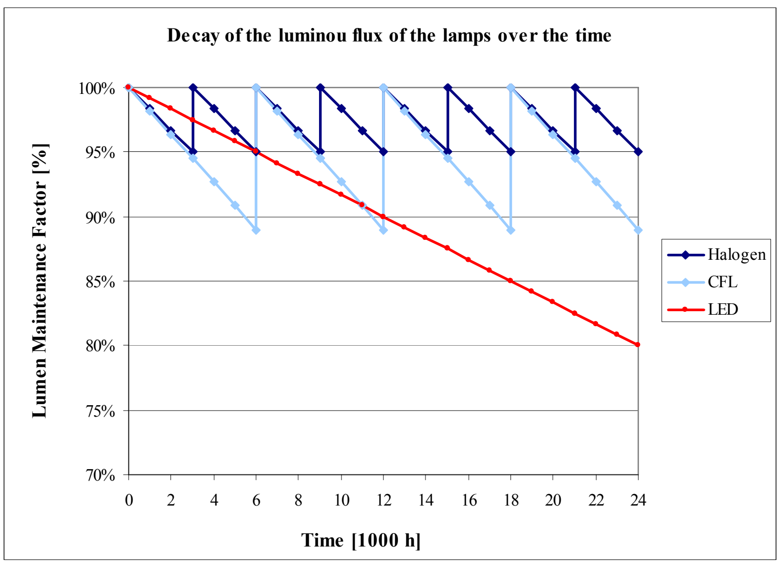


Figure 17 Lumen Maintenance Factor (LMF) of the lamps over the time

The number of lamps 'N_{Lamp}' per FU has been calculated considering the lifetime of the lamps and the number of lamps necessary for the FU (24,000 h). Successively these values have been corrected in function of the average value of the LMF and then proportionally to the needed luminous flux (400 lm) and the lamp's luminous flux, as follows:

[95] The Colour Rendering Index has not been taken into account in the provided function. The study also did not take into account the Survival Factor of the lamps, being this strictly related to the selected case-study products.
[96] The Lumen Maintenance Factor represents the proportion of light output of a lamp, compared with initial lumen output.
[97] Estimated from [CIE 97, 2005], supposing that halogen lamps have at 3000 hours the same efficiency than at 2000.
[98] From [CIE 97, 2005].
[99] Estimation from: [Van Tichelen et al., 2009].

Formula 37 $$N_{Lamps} = \frac{24{,}000\ h}{life\ time} \cdot \frac{400\,lm}{luminous\ flux} \cdot \frac{1}{LMF}$$

It is therefore calculated that the selected FU is accomplished by:

A. *4.23 CFL*;

B. *6.09 Halogen*;

C. *1.29 LED*.

D. 3.14 low mercury CFL

The materials necessary to manufacture the lamps for the four FUs are shown in Table 43.

Table 43 Materials necessary to manufacture the lamps for the four FUs

	CFL with integrated ballast	Halogen lamp 12 V	LED	CFL with low mercury content
Number of lamps per FU	4.23	6.09	1.29	3.14
Bill of Material (BOM) [g]				
Glass	150.3	12.2	13.8	111.3
Electronics	67.7		13.0	50.2
ABS	46.6			34.5
PC			13.9	
Aluminum sheet	4.2		47.5	3.1
Tungsten		3.0		
Mercury	0.021			0.0072
LED			1.9	
Steel			15.7	
Copper			0.6	
Corrugated cardboard	1,244.4	73.7	391.9	1,195.8

Concerning the assumption of the life cycle stages:

- LCI data about aluminium, ABS and PC plastics, steel, copper and cardboard refer to the ELCD database [ELCD, 2010]; LCI data of the printed circuit board, glass, LED, tungsten and mercury refer to the ecoinvent database [ecoinvent]. Impacts related to the tungsten manufacture are assumed negligible.
- the electricity consumed to assembly the lamps have been estimated on the basis of lamp's mass and reference data in[100] [Garret and Collins, 2009]: consumption of 4.2 kWh for the CFLs, 1.5 kWh for the LED and 0.1 kWh for the halogen lamp;
- no detailed data were available concerning the transportation. It was assumed that: raw materials and half-manufactured components are transported for an average distance of 300 km; transport to

[100] Assuming a consumption of 4 kWh of electricity for the manufacture and assembly of an 11W CFL (overall mass 120 g). Energy consumption for the manufacture of other lamps is estimated proportionally to the lamp's mass [Garret and Collins, 2009].

users is assumed to be 200 km; end-of-life transport is assumed to be 100 km. Impacts due to transportation refer to the ELCD database [ELCD, 2010] supposing to use an average lorry;

- energy consumption during the use is shown in Table 44 Impacts related to the production of electricity refers to the average EU-27 power mix [ELCD, 2010];
- lamps are supposed to be incinerated after their useful life. This end-of-life is not in line with the prescription of the WEEE Directive. However the preliminary study on Ecodesign implementing measures for lamps observed that 80% of the lamps are not properly recovered and treated. This end-of-life scenario allows therefore evaluating the potential effects of an incorrect handling of the mercury of the lamps. In fact, it is assumed that mercury contained into CFL is released into air after the operating life (breakage of the glass covering and the release of mercury vapours). Inventory data of the incineration processes with energy recovery refer to the ELCD database [ELCD, 2010]. A further EoL scenario will be introduced and discussed in Chapter 6.3.5

Table 44 Energy consumption of the lamps for the FU.

	CFL with integrated ballast	Halogen lamp 12 V	LED	CFL with low mercury content
Number of lamps per FU	4.23	6.09	1.29	3.14
Power [W]	10	35	8	11
Working hours [h]	6000	6000	6000	6000
Energy consumption during the use stage [kWh]	***254.0***	***1,278.7***	***61.8***	***206.9***

6.3.4 STEP 4: Comparison

The last step of the analysis concerns the comparison of the environmental impacts of the different alternatives.

Table 45 shows the impacts related to CFL, Halogen and LED lamps.

Table 45 Environmental impacts of the case-study lamps

		Abiotic Depletion Pot. (elements)	Abiotic Depletion Pot. (fossil fuels)	Acidification Potential	Eutrophication Potential	Freshwater Aquatic Ecotoxicity Pot.	Global Warming Potential	Human Toxicity Potential	Ozone Depletion Potential	Photochem. Ozone Creation Pot.	Terrestric Ecotoxicity Potential
		[kg $Sb_{eq.}$]	[MJ]	[kg SO2 $_{eq.}$]	[kg $Phosphate_{eq.}$]	[kg DCB $_{eq.}$]	[kg $CO2_{eq.}$]	[kg $DCB_{eq.}$]	[kg R11 $_{eq.}$]	[kg $Ethene_{eq.}$]	[kg $DCB_{eq.}$]
CFL	Manufacture	5.2E-03	2.1E+02	1.2E-01	2.4E-02	5.6E-01	1.8E+01	7.1E+00	2.5E-06	1.0E-02	2.6E-01
	Use	1.0E-05	1.5E+03	1.2E+00	3.8E-02	4.2E-01	1.5E+02	1.3E+01	3.6E-05	5.7E-02	2.0E-01
	End-of-life	2.0E-08	1.2E-01	5.0E-05	9.7E-06	6.7E-03	1.3E+00	1.4E-01	6.3E-11	1.0E-06	6.0E-01
	Total	**5.2E-03**	**1.7E+03**	**1.3E+00**	**6.2E-02**	**9.9E-01**	**1.7E+02**	**2.0E+01**	**3.9E-05**	**6.7E-02**	**1.1E+00**
Halogen	Manufacture	1.6E-05	-3.5E-01	2.7E-03	1.6E-04	1.2E-03	4.2E-01	3.1E-02	8.2E-08	1.5E-04	7.6E-04
	Use	5.1E-05	7.7E+03	5.8E+00	1.9E-01	2.1E+00	7.5E+02	6.5E+01	1.8E-04	2.9E-01	1.0E+00
	End-of-life	-1.8E-07	4.4E+00	-1.9E-04	-4.2E-06	-5.4E-05	4.5E-02	-3.0E-03	-2.9E-09	-1.1E-05	-2.5E-05
	Total	**6.7E-05**	**7.7E+03**	**5.8E+00**	**1.9E-01**	**2.1E+00**	**7.6E+02**	**6.5E+01**	**1.8E-04**	**2.9E-01**	**1.0E+00**
LED	Manufacture	1.0E-03	6.1E+01	3.5E-02	5.3E-03	1.1E-01	5.3E+00	1.7E+00	8.0E-07	2.8E-03	3.7E-02
	Use	2.5E-06	3.7E+02	2.8E-01	9.2E-03	1.0E-01	3.6E+01	3.1E+00	8.9E-06	1.4E-02	4.9E-02
	End-of-life	1.5E-08	1.1E-02	1.8E-05	2.9E-06	2.5E-05	4.2E-01	8.9E-04	2.5E-11	1.8E-07	1.5E-05
	Total	**1.0E-03**	**4.3E+02**	**3.2E-01**	**1.5E-02**	**2.2E-01**	**4.2E+01**	**4.8E+00**	**9.7E-06**	**1.7E-02**	**8.7E-02**
CFL with low mercury content	Manufacture	3.9E-03	1.2E+03	9.2E-02	1.8E-02	4.2E-01	1.4E+01	5.3E+00	1.9E-06	7.6E-03	1.6E-01
	Use	8.2E-06	9.4E-02	9.4E-01	3.1E-02	3.4E-01	1.2E+02	1.1E+01	3.0E-05	4.6E-02	1.6E-01
	End-of-life	1.6E-08	1.6E+02	4.4E-05	8.9E-06	2.3E-03	1.3E+00	4.9E-02	6.0E-11	6.7E-07	2.0E-01
	Total	**3.9E-03**	**1.4E+03**	**1.0E+00**	**4.9E-02**	**7.6E-01**	**1.4E+02**	**1.6E+01**	**3.2E-05**	**5.4E-02**	**5.2E-01**

It is possible to observe that:

- LED lamp has the smallest environmental impacts, compared to the other two lamp alternatives. On the other side the halogen lamp has the highest environmental burdens. CFLs have an intermediate ecoprofile;
- For all the lamp typologies, the 'use' phase is the most impacting life-cycle stage concerning the following impact categories: Abiotic Depletion (fossil), Acidification, Eutrophication, Climate changes, Human toxicity, Freshwater ecotoxicity, Ozone depletion, and Photochemical ozone creation.
- In the CFL and LED case-studies the manufacturing is dominating the Abiotic Depletion Potential (elements). Furthermore, the manufacturing contributes relevantly to the Freshwater ecotoxicity; Terrestric ecotoxicity and Eutrophication;
- The contribution of the EoL of the products to each impact category is generally negligible. The only exception is represented by the terrestrial ecotoxicity for the CFL: the disposal of the lamp (with the assumption of the release in air of the contained mercury) contributes up to 56% of the impact category. This confirms that the EoL management of mercury in CFL is relevant.
- Table 46 shows a detail of the Life Cycle Inventory concerning the emission to air of some heavy metals. It is possible to observe that base-case CFL has the highest emission of mercury (due to the lamp's disposal assumptions); halogen lamp has also very high values of mercury emission, related to the use stage. Furthermore, compared to the CFL lamp, the halogen lamps has higher emissions of other hazardous substances. LED lamp has instead the lowest emission values, due to the lower energy consumption during the use and lower impacts related to the disposal.
- Compared to the base-case CFL, the low mercury content CFL has an almost halved value of the "Terrestric ecotoxicity", mainly due to the lower release of mercury at the EoL. The low mercury content CFL has also lower values (-20%) concerning other impact categories. This is mainly due to the higher luminous efficiency of the lamp.

Table 46 Detail of the Life Cycle Inventory: overall emissions to air of some heavy metals

Emission of heavy metal	CFL (Base case)	Halogen	LED	CFL (Low mercury content
Arsenic (+V) [kg]	2.0E-05	5.7E-05	4.6E-06	1.6E-05
Arsenic trioxide [kg]	2.6E-12	1.5E-11	0.0E+00	2.1E-12
Cadmium (+II) [kg]	3.4E-06	4.5E-06	7.2E-07	2.6E-06
Chromium (+III) [kg]	4.5E-09	2.2E-08	1.1E-09	3.6E-09
Chromium (+VI) [kg]	2.6E-07	1.9E-10	5.6E-08	1.9E-07
Chromium (unspecified) [kg]	1.7E-05	2.7E-05	3.8E-06	1.3E-05
Cobalt [kg]	3.0E-06	8.0E-06	7.3E-07	2.3E-06
Heavy metals to air (unspecified) [kg]	3.3E-08	1.6E-07	8.1E-09	2.6E-08
Hydrogen arsenic (arsine) [kg]	2.3E-10	1.2E-09	0.0E+00	1.8E-10
Lead (+II) [kg]	5.2E-05	1.3E-04	1.3E-05	4.1E-05
Mercury (+II) [kg]	3.1E-05	1.7E-05	1.4E-06	1.3E-05
Nickel (+II) [kg]	5.0E-05	1.5E-04	1.2E-05	3.9E-05

Compared to the halogen lamp, CFL has higher energy efficiency with lower environmental impacts during the use stage and also lower impacts during the whole life cycle, despite of its mercury content.

The LED lamp has lower environmental life cycle impacts compared to CFL and halogen lamps. However, whether or not the LED technology (which is still under further technological development) can fully replace CFL is a technological question outside the scope of this case study, and it has be assessed separately.

It is also fundamental to verify that the new generations of CFL (in particular those with a lower mercury content) and LED would grant in the future the assumed performance in terms of life-length, energy efficiency and lumen maintenance factor.

6.4 A new scenario about CFL end-of-life

A new scenario has been defined concerning the CFL end-of-life. In particular it was supposed to handle correctly the lamp and to treat it in compliance with the WEEE Directive.

There are two main methods for removing mercury from fluorescent lamps. "*One method is to cut the end(s) off the glass tube of the lamp and remove the mercury and phosphor powder. The second method is to shred the lamp and then mechanically separate out the powder, typically in one of two ways* [EC, 2008]*:*

- *The fluorescent tubes may be crushed, sieved and separated, producing a fluorescent powder, glass and metal. The powder is heated under vacuum while simultaneously supplying oxygen to the afterburner. By varying the vacuum pressure, mercury can be extracted from the powder and collected in condensers. Approximately 99% of the mercury can be recovered* [EC, 2008]*;*
- *Alternatively, while the fluorescent tubes are crushed, a filter can trap the mercury vapour that can then be either disposed of or sent for recycling. The glass can be used to make other glass products, and the end pieces (normally consisting of either brass or aluminium) of the tubes can be sold on to scrap metal processors*" [EC, 2008].

In our study, the end-of-life scenario supposed that the CFL is separately collected and addressed to a shredding process with mercury vacuum recovery. Successively, the glass and metals are addressed to recycling while plastics are incinerated.

Concerning the EoL treatment processes, it is assumed that:

- the overall transported distance amounts to 500 km. This includes all the transportation steps as: take back option of the retailers for separate collection, transport to mercury treatment plants, and transport of residuals to recycling plants. The high value of the overall distance reflects the low number of specialized treatment facilities in Europe[101].

[101] A document of the EC listed the facilities for the treatment of mercury contaminated wastes (partial data obtained from returned questionnaires) [EC, 2008]. It is possible to observe that various countries are not provided with such plants. Furthermore the distribution of the facilities is not homogeneous in the EU. On average, it is realistic to suppose very long transportations to correctly handle the end-of-life of an exhausted CFL in EU.

- The resources inputs per lamp necessary for the shredding amounts to [Garret and Collins, 2009]: 0.00032 kWh of electricity; 0.00018 litre of diesel; 0.00011 kg of polycarbonate plastic; 3.04E-03 g of steel.
- The resources inputs per lamp necessary for the treatment in the specialized facility amounts to [Garret and Collins, 2009]: 0.018 kWh of electricity; 0.0014 kg of nitrogen; 0.0028 kg of oxygen. The recovered mercury (supposed to be 99% of the lamp content) is then replacing primary mercury. The only output of the treatment facilities are the plastic wraps, which are supposed to be incinerated.

Results of the new scenario have been compared with those of the CFL base-case (Table 47).

Table 47 Environmental impacts of the different lamps (Hg recycling scenario)

		Abiotic Depletion Pot. (elements)	Abiotic Depletion Pot. (fossil fuels)	Acidification Potential	Eutrophication Potential	Freshwater Aquatic Ecotoxicity Pot.	Global Warming Potential	Human Toxicity Potential	Ozone Depletion Potential	Photochem. Ozone Creation Pot.	Terrestric Ecotoxicity Potential
		[kg $Sb_{eq.}$]	[MJ]	[kg SO2 $_{eq.}$]	[kg $Phosphate_{eq.}$]	[kg DCB $_{eq.}$]	[kg $CO2_{eq.}$]	[kg $DCB_{eq.}$]	[kg R11 $_{eq.}$]	[kg $Ethene_{eq.}$]	[kg $DCB_{eq.}$]
CFL	Manufacture	5.2E-03	2.1E+02	1.2E-01	2.4E-02	5.6E-01	1.8E+01	7.1E+00	2.5E-06	1.0E-02	2.6E-01
	Use	1.0E-05	1.5E+03	1.2E+00	3.8E-02	4.2E-01	1.5E+02	1.3E+01	3.6E-05	5.7E-02	2.0E-01
	End-of-life	2.0E-08	1.2E-01	5.0E-05	9.7E-06	6.7E-03	1.3E+00	1.4E-01	6.3E-11	1.0E-06	6.0E-01
	Total	**5.2E-03**	**1.7E+03**	**1.3E+00**	**6.2E-02**	**9.9E-01**	**1.7E+02**	**2.0E+01**	**3.9E-05**	**6.7E-02**	**1.1E+00**
CFL (with Hg recycling)	Manufacture	5.2E-03	2.1E+02	1.2E-01	2.4E-02	5.6E-01	1.8E+01	7.1E+00	2.5E-06	1.0E-02	2.6E-01
	Use	1.0E-05	1.5E+03	1.2E+00	3.8E-02	4.2E-01	1.5E+02	1.3E+01	3.6E-05	5.7E-02	2.0E-01
	End-of-life	*-8.4E-07*	*-5.1E+00*	*1.2E-05*	*1.4E-07*	*-3.3E-05*	*1.3E+00*	*3.3E-06*	*-3.3E-08*	*1.2E-06*	*5.0E-03*
	Total	**5.2E-03**	**1.7E+03**	**1.3E+00**	**6.2E-02**	**9.8E-01**	**1.7E+02**	**2.0E+01**	**3.9E-05**	**6.7E-02**	**4.7E-01**

Concerning the end-of-life stage, it is possible to note the new recycling scenario has lower impacts for almost all the impact categories[102] but with relevant reduction related to the "Terrestric ecotoxicity" impact category.

This new scenario shows the potential relevance of a correct handling of end-of-life of CFL. The recovery and recycling of mercury and other valuable resources is an important way to avoid the dispersion into air of the hazardous mercury content and, at the same time, a way to diminish resource depletion and other impacts. It is also important that consumers should be informed on the risks of an incorrect disposal of CFL, on the risks about mercury dispersion and on the procedures and alternative for the CFL collection and recycling. Clear information on this topic could be publicized and clearly showed in the lamps packaging and instruction for the use.

[102] Smaller variations are observed for the "climate chance" and the "photochemical ozone creation" impacts, due to the transportations and the treatment for the shredding.

6.5 Summary

The Chapter presents a methodology for the assessment of the use of hazardous substances into products. The methodology is based on a multi-criteria life-cycle approach and it aims at assessing how the content of hazardous substances can affect the ecoprofile of a case-study product. The methodology can be useful to identify ‘key’ components of the product that have higher environmental impacts. Design requirements could be potentially set for these ‘key’ components to reduce their impacts at the design stage.

It is important to highlight that the proposed methodology does not consider all the potential impacts related to the case-study product. The analysis cannot be therefore applied to formulate general conclusion about the products and technologies. Furthermore, the results of the analysis are strictly related to the selected case-studies and to their representativeness. A more detailed study of a product category should be based on the comparison of different case-studies and under different life-cycle scenarios.

The methodology has been applied to a substance regulated by the RoHS Directive 2002/95/EC and the following exemptions. However, the methodology is fully applicable to the assessment of the use of SVHC (as regulated by the REACH) and also of other hazardous substances that are currently not regulated.

The presented case-study concerns the assessment of the mercury content in Compact Fluorescent Lamps (CFL). A base case-study ‘CFL‘ has been compared with two exemplary ‘halogen’ and ‘LED’ lamp. The scope is to points out how the different use/release of hazardous substances during the life-cycle modifies the ecoprofile of the product.

The case-study shows that CFL, despite of their mercury content, have higher energy efficiency that causes lower environmental impacts during the use stage and also over their entire life cycle, compared to the halogen lamp.

LED lamps have a lower environmental life cycle impacts compared to CFLs. However, whether or not the LED technology (which is still under further technological development) can fully replace CFL is a technological question outside the scope of this case study, and it has to be assessed separately.

From the analysis it has been concluded that requirements concerning the limitation of the use of hazardous substances should be assessed in a life cycle perspective, assessing in detail the function of the substances in the product and the related life cycle impacts.

7 Ecodesign requirements for products

7.1 Potential Ecodesign requirements for products

The present Chapter summarizes and couples the results of the previous chapters and the outcomes of the Deliverable 1. Scope of the Chapter is the identification of possible requirements for the Ecodesign that could contribute to improvement of resource efficiency and, in particular, the improvement of product's RRR, the recycled content of products and the optimisation of the use of priority resources.

The potential requirements will implement the measurement/verification methodologies, procedures and outcomes of the previous Chapters (for a complete overview of indices cited in the requirements, see the section "*Summary of the developed indices*" - *page 11*).

The potential requirements have a 'general' structure and, therefore, potential extensible to different product categories. Some notes underline when and how differentiations are needed in function of the considered product category.

The potential requirements have been subdivided into two parts:

- the first part (Chapter 7.2) include the main requirement built directly on the proposed methodology for the measurement of RRR, recycled content and prioritisation of resources;
- the second part (Chapter 7.3) include instead other additional requirements that aims at indirectly improve *RRR* (by improving, for example, the product disassemblability, the labelling of potential harmful components, the compatibility among different materials, etc.).

7.2 Main Requirements about the project's parameters

7.2.1 Potential requirements on the RRR of the product

The previous chapters described and applied the methodologies for the measurement of *RRR*. In particular two set of indices have been introduced: one referring to mass ratio and the second one related to the potential benefits achievable by reuse/recycle/recovery. It was observed that this second set is more consistent and representative, and it is therefore preferred for the setting of potential requirements.

Potential requirements (requirements 1, 2 and 3) concern the declaration of the measured values of the '*RRR* Ratio indices' or, analogously, the value of the 'RRR Benefit Ratio' indices. Requirements 4, 5 and 6 set minimum thresholds for the above mentioned indices.

Requirement 1. Declaration of the ‘Reusability Benefit Ratio’ (or of the ‘Reusability Ratio’)

The manufacturer has to declare the value of the ‘Reusability Benefit Ratio’ (or ‘Reusability Ratio’) of the product. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority.

(Details about the documents to be provided are discussed in Chapters 2 and 3).

Requirement 2. Declaration of the ‘Recyclability Benefit Ratio’ (or of the ‘Recyclability Ratio’)

The manufacturer has to declare the value of the Recyclability Benefit Ratio (or the Recyclability Ratio) of the product. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority.

(Details about the documents to be provided are discussed in Chapters 2 and 3).

Requirement 3. Declaration of the ‘Energy Recoverability Benefit Ratio’ (or of the ‘Energy Recoverability Ratio’)

The manufacturer has to declare the value of the ‘Energy Recoverability Benefit Ratio’ (or the ‘Energy Recoverability Ratio’) of the product. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority.

(Details about the documents to be provided are discussed in Chapters 2 and 3).

Requirement 4. Threshold of the Reusability Benefit Ratio (or of the Reusability Ratio)

The product shall have a minimum 'Reusability Benefit Ratio' (or a minimum 'Reusability Ratio') of X%[103]. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority. (Details about the documents to be provided are discussed in Chapters 2 and 3).

Requirement 5. Threshold of the Recyclability Benefit Ratio or of the Recyclability Ratio)

The product shall have a minimum 'Recyclability Benefit Ratio' (or minimum 'Recyclability Ratio') of X%[104]. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority. (Details about the documents to be provided are discussed in Chapters 2 and 3).

Requirement 6. Threshold of the Energy Recoverability Benefit Ratio (or of the Energy Recovery Ratio)

The product shall have a minimum Energy Recoverability Benefit Ratio (or minimum Energy Recoverability Ratio') of X%[105]. (Calculations have to be based on the methodologies introduced in Chapters 2 and 3).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority. (Details about the documents to be provided are discussed in Chapters 2 and 3).

It is important to note that threshold requirements (as requirements n° 4, 5 and 6) should be checked from a life-cycle perspective, to avoid the potential shifting of burdens (e.g. the increase of the energy consumption due to the reuse of components in the EuP).

[103] The percentage X should be fixed in function of the product category.
[104] The percentage X should be fixed in function of the product category.
[105] The percentage X should be fixed in function of the product category.

Other requirements could be set concerning the disassembly of key components of the products. Key components could be:

- components with a relevant mass (in line with the methodologies for the calculation of the 'RRR Ratio' indices) or
- components containing substances that can grant relevant environmental benefits if reused/recycled/recovered (in line with the methodologies for the calculation of the 'RRR Benefits Ratio' indices)

Requirement 7. Manual disassembly of the key components

Key components of the product shall be easily accessible to professionally trained recyclers (using the tools usually available to them) in order to facilitate their removal.

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority.

Supporting documentation can include:

- BOM of the component;

- Disassembly report of the product, with a detail of the considered component.

The requirement n°7 aims at improving the disassembly of the key components of the product. For example for the HDD case-study the Printed Circuit Board can be considered a potential 'key component', due to the content of substances (as e.g. gold) that can grant relevant environmental benefits if recycled. Possible requirements concerning other key components should be identified 'case-by-case' for other product category.

Note that the requirement n° 7 could potentially include also some thresholds regarding the disassembly of the products, to be expressed for example in 'kg of component per minute' that can be manually separated.

7.2.2 Potential requirements on the Recycled content of the product

Chapter 4 analyzed the methodology for the measurement of the recycled content of a product (or its components). Some potential requirements for the product design are suggested. The requirements regard:

- The declaration of the recycled content of the product or the achievement of minimum thresholds for the recycled content;
- 'post-consumer' recycled content of some specific materials/components.

The introduction of post-consumer 'recycled content' requirements could contribute to increase the demand for the secondary good and support in this way their recycling. For the case study of Chapter 5, this is particularly relevant for materials that have a low value after disposal (as plastics)[106].

Further thresholds could be identified for other material typologies contained in the product category under study whose recycling could be promoted by recycled content requirements (e.g. technical glass).

Requirement 8. Declaration of the recycled content of plastics.

Manufacturer has to declare the 'post-consumer' recycled content of plastics. (Calculation has to be carried out with methodology described in Chapter 4).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority. (Details about the documents to be provided are discussed in Chapter 4).

Other potential requirements could be set on minimum thresholds of recycled content that the manufacturers have to achieve for some product's components (e.g. plastic components).

Requirement 9. Threshold of the recycled content of plastics.

The product shall have at least[107] X% of post-consumer recycled plastic content (measured as percentage of the overall mass of plastics components). (Calculation has to be carried out with methodology described in Chapter 4).

Verification:

Self declaration of the manufacturer, supported by technical documentation available before the product is put into the market and provided on request to the Market Surveillance Authority. (Details about the documents to be provided are discussed in Chapter 4).

7.2.3 Potential requirements on the content of hazardous substances

Chapter 5 discussed the methodology for the assessment of the use of hazardous substances. Some potential Ecodesign requirements could be set concerning:

- The disassembly of key components (those containing the hazardous substances);

[106] Recycled content requirements for some materials can be, in some cases, less effective. As discussed in Chapter 4.4, metals for example have already a medium/high level of recycled content and the setting of specific requirements would not further promote the recycling.
[107] The percentage X should be fixed in function of the product category.

- The declaration of the hazardous substances contained in the product (or in some specific 'key component');
- The maximum content of hazardous substances in the product (or some specific components).

Some illustrative requirements have been described as follows.

Requirement n° 10 refers to the disassembly of key components (those containing relevant qualities of potential hazardous substances) as for example, the printed circuit board in the HDD case-study.

Requirement n° 11 refers to the declaration of the hazardous substances in key components, by, for example, reporting a detailed BOM.

Requirement n° 12 sets the maximum quantity of hazardous substances contained into a target component. For example, the requirement can be referred to the content of flame retardant into plastic components.

Requirements similar to the previous ones could be indentified for other potential hazardous substances or components.

Requirement 10. Manual disassembly of components containing hazardous substances

Components containing hazardous substances shall be easily and safely removable[108].

Verification:

Self declaration of the manufacturer supported by technical documentation that details the disassembly of the component (e.g. a disassembly report). The declaration has to be available before the product is put into the market and provided on request to the Market Surveillance Authority. The authority can also undertake laboratory test to check the truthfulness of the declaration.

Requirement 11. Content of hazardous substances into key components.

Manufacturer has to declare the content of hazardous substances contained in the component. The listed substances should include substances regulated by European Directives and Regulation (e.g. RoHs or REACH) and substances classified with the following risk phrases: R45, R46, R60, R61, R50/53, R51/53 as defined in Council Directive 67/548/EEC.

Verification:

Self declaration of the manufacturer, supported by technical documentation that details the content of the hazardous substances. The declaration has to be available before the product is put into the market and provided on request to the Market Surveillance Authority. The authority can also undertake laboratory test to check the truthfulness of the declaration.

[108] Components containing hazardous substances shoud be, for example, the printed circuit boards.

Requirement 12. Limit of hazardous substances.

Target components[109] heavier than X [g][110] shall not contain more than Y%[111] by mass of substances that are classified with the following risk phrases[112]: R45, R46, R60, R61, R50/53, R51/53 as defined in Council Directive 67/548/EEC.

Verification:

Self declaration of the manufacturer supported by technical documentation that details the content of the hazardous substances. The declaration has to be available before the product is put into the market and provided on request to the Market Surveillance Authority. The authority can also undertake laboratory test to check the truthfulness of the declaration.

It is important to note that threshold requirements (as requirement n° 12) should be checked from a life-cycle perspective, by assessing all the functions that the substance have in the product. For example, it should be considered/assessed the reduction of risks of fire due to the use of flame retardants and also the availability of replaceable substances that are not hazardous.

[109] For example, the target components could be the plastic parts of the product.
[110] The percentage X should be fixed in function of the product category.
[111] The percentage Y should be fixed in function of the product category.
[112] Note that these risk phrases are only illustrative and the list could be modified in function of the considered product category.

7.3 Other requirements about the Ecodesign of the product

The following sections illustrate some potential Ecodesign requirement that can potentially affect various parameters simultaneously (e.g. the RRR, the use of priority resources or the use of hazardous substances).

7.3.1 Potential requirements concerning the Bill of Materials and product's composition

The Bill of Material (BOM) represents a fundamental document for the methodologies developed in the present Deliverable. The BOM collects the key information that is necessary for the assessment of the project's parameters. We can synthesize that a detailed and precise BOM is the first step to improve resource efficiency. The knowledge of a product is, in fact, the first step to allow reuse/recycle/recovery.

The BOM, with the related disassembly schemes and materials details, should be annexed to the other technical specifications of the products. This would produce several benefits, as:

- It is publicized the composition of the product. On the basis of such data, external companies could decide if and what components could be suitable for reuse/recycle/recovery;
- The disassembly schemes and the description of assembly elements could simplify the disassembly of the product at the EoL by third party subjects;
- The BOM contains a description of also substances potential harmful for the health as heavy metals or toxic flame retardants. Their identification in the product component could better address the actions/solutions to handle the product at the EoL;
- Designers that have to draft the BOM of their products are pushed to analyze the disassembly of the product and potential problems that could arise. The BOM scheme proposed in the present deliverable could help designers to indentify solutions to improve the disassembly at the EoL ('Design for disassembly');
- A detailed description of the product composition is also a first step to make a Life Cycle Assessment (LCA) of the product. A detailed published BOM could also contribute to stimulate/facilitate the accomplishment of the LCA studies.

Furthermore, the manufacturers should improve the marking and labelling of critical components of their products. This would have the effect to simplify the identification of the component for different purposes including:

- Substitution of the component (during the operating time) if it is subject to high wear;
- Disassembly of the component and sorting for the reuse/recycle/recovery;
- Identification of potential harmful components.

Some illustrative Ecodesign requirements can be introduced concerning, for example:

- The description of the BOM and the product's characterisation;
- The marking of plastic parts.

Requirement 13. BOM

Manufacturers have to compile a BOM of the product. Potential information to be included is:

- the detail/description of each component,
- the material composition of the components;
- the content of hazardous substances regulated by the RoHS Directive or SVHC regulated by the REACH (content higher than 0.1% in mass of the component);
- the detail of flame retardants embodied into plastics (is their mass id higher than a fixed threshold of the component) and their risk phrases as defined in Council Directive 67/548/EEC;
- the detail of labels, adhesives, paints and inks on components (if their mass is higher than a fixed threshold of the component). In this case, companies have to assess the compatibility of such additional elements with the component's reusability/recyclability/recoverability;
- the disassembly report that illustrate the assembly elements, the procedures to disassembly and the timing for the disassembly.

Verification:

The BOM has to be available on request to the Market Surveillance Authority and, potentially, to other stakeholders[113].

Requirement 14. Identification of plastic components.

Plastic components with a mass higher than[114] ***X*** [g] shall be marked with a material code in accordance with the identification and marking requirements of ISO 11469:2000.

Verification:

- Manufacturer's declaration about the compliance with the ISO 11469:2000 marking;
- Record of visual inspection

[113] Depending on the considered product category, it should be defined to which stakeholders the information should be disclosed (e.g. recyclers or public disclosure).
[114] The value of X should be defined in relation with the product category.

7.3.2 Potential requirements concerning the materials contamination

As previously discussed, the contamination among materials is a key issue for *RRR,* influencing both 'RRR Ratio' indices and 'RRR Benefit Ratio' indices.

Designer should focus their attention on:

- Identify possible sources of contamination;
- Assess if and how contaminations could interfere with the reuse/recycle/recovery of the product.

Some additional requirements could be set to reduce/avoid contamination.

Requirement 15. Contamination of Plastics

Plastic enclosures shall not contain moulded-in or glued-on metal inserts unless these are easy to remove by one person alone with commonly available tools.

Verification:

a) Declaration of the manufacturer with a supporting documentation (e.g. BOM) that demonstrates that the plastic enclosures do not incorporate glued/moulded metal inserts, or

b) Declaration of the manufacturer with a supporting documentation that demonstrates that the plastic enclosures are easily removable. The supporting documentation included e.g. the disassembly report with a detail of the procedure for the removal of metal inserts.

Requirement 16. 'Monomaterial'

Only one plastic material type shall be used in each plastic enclosure part with a mass higher than X [g][115].

Verification:

a) Declaration of manufacturer supported by technical documentation (e.g. a BOM of the product) available before the product is put into the market and provided on request to the Market Surveillance Authority, or

b) Declarations from the suppliers (for purchased product), available before the product is put into the market and provided on request to the Market Surveillance Authority.

[115] The minimum mass of the plastic component should be in function of the product category.

Requirement 17. Compatibility of labels with recycling.

Labels, inks, glues, adhesives and paints with a mass higher that X%[116] of the component shall be compatible with the recycling, or they shall be easily removable without leaving residues that could interfere with the reuse/recycle/recovery.

Verification:

a) Declaration from manufacturer that the used labels, ink, glue and adhesive are compatible with the component recycling. The declaration shall be supported by supporting technical/scientific documentation proving the compatibility, or

b) Declaration from the manufacturer that the labels, inks, glues and adhesives can be easily removed. The declaration has to be supported by a description of the procedures for the removal of the labels.

[116] The threshold mass should be defined case-by-case

7.4 Possible problems related to the potential Ecodesign requirements

The potential requirements that have been previously discussed are based on a life-cycle approach. The methodologies for the measurement of RRR embody the 'prioritisation' of resources based on the potential environmental benefits related to their reuse/recycle/recovery. However they do not consider all the physical/chemical characteristics of the materials. For example they relate exclusively to material and energy consumption due to materials and components embodied in the products, respectively as being recyclable/reusable/recoverable at the end-of-life, but not considering the products use phase.

It is therefore important to highlight that the potential Ecodesign requirements here discussed could potentially cause design measures that worsen the product's overall environmental life cycle performance, by causing a shifting of burdens. For example, the reuse of some EuP's components could cause higher energy consumption during the use phase.

In order to avoid potential 'shifting of burden' it is recommended the adoption of a life cycle check for the assessment of some Ecodesign requirements. This could be for example the case of minimum thresholds concerning the 'RRR indices' and the 'RRR Benefit Ratio' indices.

Furthermore, some substances could have a specific function in a product that. For example some toxic substances can allow lower energy consumption during the use phase (e.g. mercury in CFL); other substances, as the flame retardants, can be relevant for some environmental impact categories but, on the other side, they can reduce the fire risks and the related potential impacts. The restriction of the use of hazardous substances by setting minimum thresholds should therefore be checked following a life cycle approach, comparing also different technologies and potential replaceable substances.

7.5 Summary of the requirements

The previous chapters illustrate some exemplary potential requirements with the purpose of improving the resource efficiency of products during the design phase, with special attention to the management of their EoL.

These requirements have been selected to identify those components that could grant the highest environmental benefits (in terms of avoided burdens for the otherwise required production of primary materials).

We underline that all the identified potential requirements have a general structure and they are generally applicable to a wide range of product categories (the variability of the requirement depending on the selected product category, has been underlined in the footnotes of the requirements).

Reflecting on these individual findings, it can be concluded that the analysed Ecodesign criteria are important components for resource efficiency measures in product policy.

The potential requirements can be gathered in three main groups (Table 48):

- Requirements concerning the description of the product ('*Descriptive Requirements*');

- Requirements concerning declaration by the manufacturer (‘*Declarative Requirements*’);
- Requirements concerning minimum threshold to be achieved (‘*Threshold Requirements*’).

Table 48 Synthesis of the potential Ecodesign requirements

n°	**Potential Requirements** *Description*	**Descriptive Requirement**	**Declarative/ Demonstrative Requirement**	**Threshold Requirement**
1	Declaration of the ‘Reusability Benefit Ratio’ (or the Reusability Ratio)		X	
2	Declaration of the ‘Recyclability Benefit Ratio’ (or the ‘Recyclability Ratio’)		X	
3	Declaration of the ‘Energy Recoverability Benefit Ratio’ (or the ‘Energy Recoverability Ratio’)		X	
4	Threshold of the Reusability Benefit Ratio (or the Reusability Ratio)			X
5	Threshold of the Recyclability Benefit Ratio (or the ‘Recyclability Ratio’)			X
6	Threshold of the Energy Recoverability Benefit Ratio (or the ‘Energy Recoverability Ratio’)			X
7	Manual disassembly of key components	X	X	
8	Declaration of the recycled content of plastics.		X	
9	Threshold of the recycled content of plastics.			X
10	Manual disassembly of components containing hazardous substances	X	X	
11	Content of hazardous substances into key components	X		
12	Limit of hazardous substances into plastics			X
13	BOM	X		
14	Identification of plastic components	X		
15	Contamination of plastics			X
16	‘Monomaterial’			X
17	Compatibility of labels with recycling.			X

The first group refers to information that the manufacturer has to provide. As previously observed and discussed in several chapters of the present document, the proposed methodologies for the measurement of *RRR* and recycled content need a detailed description of the product and its content.

The second group refers to declarations that manufacturers have to provide concerning the accomplishment of some scopes. The requirements concern the improvement of the product's ‘disassemblability’, the accessibility to ‘key’ components, or the declaration of the estimated values of indices concerning the RRR or the recycled content.

The third group refers to minimum thresholds of the specific parameters that have to be achieved by the manufacturers/designers.

Note that some requirements (as those related to the disassembly) belong to various categories.

The ‘threshold requirements’ represents a sensible category of requirements. These, in fact, fix quantified targets that should be achieved by manufacturers during the design of the product. The suggested threshold requirements concern:

- The minimum targets concerning the ‘RRR Ratio’ indices and the ‘RRR Benefit Ratio’ indices
- The Recycled content

- The maximum content of hazardous substances in the product (or its components)
- The restriction of the use of potential contaminating materials in the components that could interfere with their reuse/recycling/recovery.

Some of the threshold requirements are critical because these could affect other stages of the product's life cycle. For example, the reuse of some components could cause the increase of energy consumption of EuP in the use stage.

A life cycle check is therefore necessary preliminary to the setting of some of the requirements[117] to avoid potential "shifting-of-burdens".

It is important to underline that requirements about ‘RRR Ratio’ indices and ‘RRR Benefit Ratio’ indices can coexist because these have different targets: the first ones aims at reducing the overall mass of waste produced at the EoL of the products; the last ones aims at Reusing/Recycling/Recovering the components of the product that can grant the largest environmental benefits.

Also declarative and threshold requirements can coexist. The declarative requirements can be useful to communicate the effective targets that have been achieved by the manufacturer. These targets could be higher than the minimum thresholds. Furthermore, the adoption of declarative requirements could be preliminary to the setting of threshold requirements.

Potential requirements on the ‘post-consumer’ recycled content have been identified for plastics. However requirements concerning additional materials could be set concerning e.g. technical glass.

Requirements concerning the overall recycled content of the product should instead be avoided. Such requirements, in fact, merge information concerning different materials and they risk generating confusion and being ineffective in term of promotion of the recycling of materials.

7.6 Conclusions and recommendations

The present chapter identified and discussed a list of potential Ecodesign requirements concerning the investigated parameters: RRR, Recycled content, Use of priority resources and Use of hazardous substances. All the discussed requirements are listed in Chapter 7.5.

Note that the list includes also some requirements that can potentially affect various parameters simultaneously (Chapter 7.3). These ‘multiple-targets’ requirements have been based on similar requirement already implemented in some environmental labelling schemes[118].

All the discussed requirements are illustrative and the have to be considered as ‘prototypes’ potentially adaptable to different product categories.

The setting of the requirements should check, in a life cycle perspective, the significance of the proposed requirement and the potential risk of shifting of burdens. The life cycle check should assess

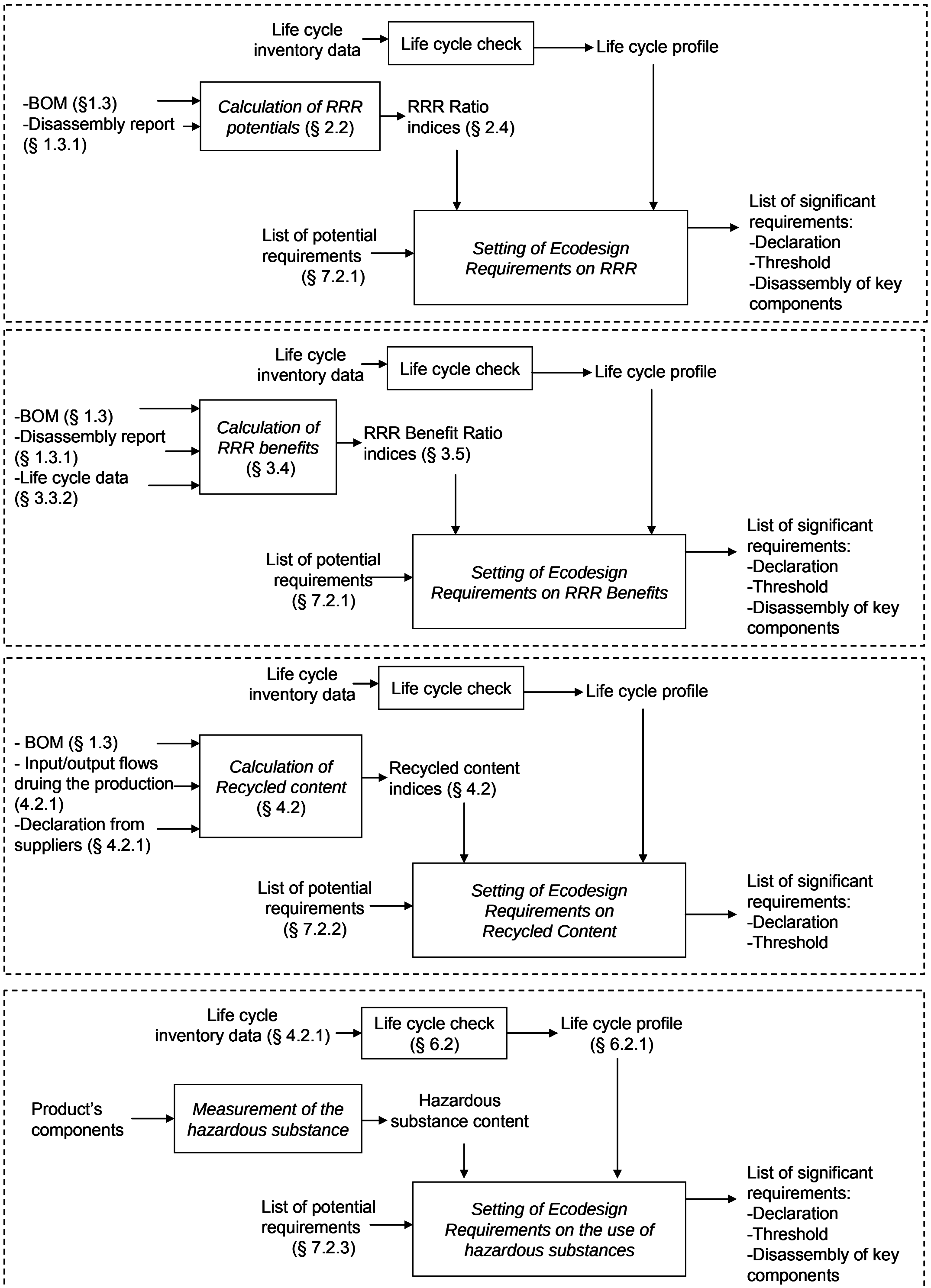
[117] For example, the life cycle check is needed for requirements concerning: the thresholds of RRR indices, the thresholds of RRR Benefit indices and the limits of the use of hazardous substances.

[118] For example, the EU Ecolablel criteria for “Personal computers and portable computers”, “Washing machine”, “Refrigerators”, “Vacuum cleaner” and “Televisions”, or the IEEE standard 1680.1 for the “Environmental Assessment of Personal Computer Products”.

different case-study products and technologies. Particular attention should be focused on threshold requirements.

Figure 18 illustrates how the list of the potential requirements and the developed methodologies could be used as input data for the setting of the Ecodesign requirements for a considered product category (e.g. during a preparatory study for the development of the implementing measures).

Figure 18 Use of the developed methodology for the setting of potential Ecodesign requirements



Final Conclusions and Recommendations

This report illustrates the methodologies and the verification procedures to estimate the Reusability/Recyclability/Recoverability (*RRR*), the use of priority resources, the recycled content of materials and the use of hazardous substances in products.

'Reusability/Recyclability/Recoverability' indices

The *RRR* are not measurable 'physical' properties but they are 'potentials' to be estimated on the basis of the characteristics of the products and additional study's assumptions. The measurement methodology is based on the collection of information about the product structure and its material composition. This information is then gathered to obtain the RRR indices.

The calculation of the indices for *RRR* requires, in a first stage, information concerning:

- The structure of the product and 'disassemblability' of the components,
- The contamination among different materials,
- The degradation of physical/chemical properties of the materials,

Some exemplary tables for the calculation of the disassemblability, contamination and degradation have been provided. However, these tables are only illustrative of the proposed approach and they should be further refined before to be suitable for the use into EU policies. However, the proposed indices have a modular structure (indices obtained as the product of different sub-indices). The modularity of the indices allows including or excluding some of the sub-indices without compromising the methodology itself. Furthermore, new sub-indices can be added in future, reflecting additional aspects that have not been investigated at this stage. Analogously, some indexes can be modified or removed on the basis of the expected targets of the decision-makers, effectiveness, and other considerations.

Resource prioritisation and 'Reusability / Recyclability / Recoverability Benefits' indices

'Mass based' indices are not differentiated by materials and they do not capture the substantially different environmental benefit of the reuse/recycling/recovery of different materials. More effective indices are derived by integration of such a differentiation via a prioritisation/valorisation of resources.

Therefore a new set of indices has been proposed: the '*RRR* Benefits Ratio' indices.

Differently form mass based indices (e.g. the RRR Ratios or the indices introduced by the ISO 22628), the '*RRR* Benefit Ratio' indices enclose life-cycle data about the materials and information concerning the environmental benefits related to the potential reuse/recycle/recovery of the materials.

The new indices represent a progress '*beyond the current state of art*' in legislation, developed on the basis of newer insights of the scientific and technical literature.

The application of the methodology confirmed that some components can be not relevant in terms of 'mass fraction index' but they can be relevant in terms of 'potential environmental benefits' (e.g. gold in printed circuit board). Furthermore, it can be observed that the recycling of a product should be addressed to key components, meaning those components that can grant higher benefits when recycled.

Being not possible to establish where the product will be treated at its EoL, the methodology has to be based on an average European scenario. On such purpose, the life cycle data of the production processes have to refer to the average EU technology mix. When different alternative are feasible (e.g. for the energy recovery) a potential feasible scenario has to be assumed.

The RRR Benefits Ratio indices can be calculated referring to any life cycle impact category. In the present report their calculation has been illustrated on the GWP impact category.

The verification of the calculation of the 'RRR indices and the 'RRR Benefit Ratio' indices is based on self-declarations supported by technical documentation available before the product is put into the market and provided on request (e.g. a check by the competent body).

The declarations could be verified e.g. by a Market Surveillance Authority (MSA) that can check the truthfulness of provided information (e.g. BOM, disassembly scheme and disassembly report) and successively would follow the calculation done by the manufacturer in the 'calculation data sheet'.

Recycled content

The present deliverable introduces a methodology for the measurement of the recycled content of the product. Differently from *RRR* that are potentials, the recycled content is a physical characteristic of the product that does not change over the time. However it cannot be directly measured but it needs to be calculated/estimated from supply-chain information:

The proposed methodology for the measurement of the recycled content is based on the collection and elaboration of information about the product components and their 'manufacturing history'. The recycled content is estimated as the fraction in mass of the product (or its component) that is manufactured with recycled materials.

Different typologies of 'recycled content indices' have been defined relatively, for example, to pre-consumer or post-consumers recycling, or related to one single material or on average of different materials.

The deliverable discussed about the opportunity of setting requirements about the recycled content of product with the scope of fostering the recycling. It has been concluded that the requirements should focus mostly on 'post-consumer' recycled content related to specific materials. An 'average' recycled content related to the whole product would cause, instead, the aggregation of information from different materials with a relevant loss of reliability of the index.

Recycling and recycled content - which measure is suitable when?

A separate and more detailed discussion is required to systematically identify materials for which a higher recycled content is the right measure (mainly those which otherwise would not be recycled and are disposed to landfills or partly undergo energy-recovery, such as post-consumer plastics) and for which an increased recyclability is key (mainly those which have a high demand for secondary material beyond availability, i.e. most materials with a growing market).

This discussion and the related decisions are important to ensure the selected measures and specifically covered materials actually improve the overall environmental situation. On general level it can however be said, that requirements about the recycled content should mainly regard materials that have a low value after the recycling. Such requirements could contribute to increase the demand of recycled material.

The requirements could also boost the technology development for the recycling of such material. Analogously the recycled content could also regard priority materials in order to foster their recycling (when technologically possible) and contribute to reduce to the supply risks and the related environmental impacts.

Case study analysis: hard disk drive

The above mentioned methodologies for the estimation of the *RRR* potentials and the recycled content have been illustrated on a case-study: a hard disk drive. The case study discussed the key issues of the calculation process. Furthermore it identified the components of the product that are more relevant in terms of their environmental impacts and in terms of potential benefits related to their reuse/recycling/recovery.

Hazardous substances

The last part of the methodological analysis concerns the assessment of the use of hazardous substances in the products. The use of some hazardous substances has been already regulated by the EU legislation (e.g. by the RoHS Directive and the REACH Regulation). However, some exemptions have been introduced for some product categories because a certain content of hazardous substances is necessary for the operation of some specific technologies.

The assessment of the use of hazardous substances has to be related to the life-cycle performance of the studied product. Performances should be assessed by a multi-criteria approach (i.e. based on a comprehensive set of various impact categories).

The scope of the analysis is to points out how the different use/release of hazardous substances during the life-cycle modifies the ecoprofile of the product, i.e. it goes beyond the pure content of potential harmful substances but includes their actual release over the life cycle as well as effects on other product characteristics including use performance/efficiency etc.

This approach is also useful to identify 'key' components of the product that have the highest environmental impacts. Design requirements could be potentially set for these 'key' components to improve their 'disassemblability' and their treatment at the EoL.

The methodology has been illustrated on the case study of Compact Fluorescent Lamps compared to alternative products (halogen lamps and Light Emitting Diode – LED lamp).

Synthesis of the results and potential requirements

The results of the previous 'methodological' and 'case-study' analyses have been the basis to define possible Ecodesign requirement for the products. Some potential requirements have been finally identified. All the discussed requirements are illustrative and the have to be considered as ‘prototypes’ potentially adaptable to different product categories.

The potential requirements can be gathered in three main groups:

- Requirements concerning the description of the product (‘*Descriptive Requirements*’);
- Requirements concerning declaration by the manufacturer (‘*Declarative Requirements*’);
- Requirements concerning minimum threshold to be achieved (‘*Threshold Requirements*’).

The first group refers to information that the manufacturer has to provide. Such requirements have the scope to provide useful information that could address reuse/recycle/recovery of the product at his EoL.

The second group refers to declarations that manufacturers have to provide concerning the accomplishment of some scopes. The potential requirement can concern the improvement of the product’s ‘disassemblability’, accessibility to ‘key’ components, or the declaration of the estimated values of indices concerning the *RRR* or the recycled content.

The third group refer to minimum thresholds of the specific parameters that have to be achieved by the manufacturers/designers.

The ‘threshold requirements’ represents a sensible category of requirements. These, in fact, fix quantified targets that should be achieved by manufacturers during the design of the product. The suggested threshold requirements concern:

- Minimum targets for the ‘RRR Ratio’ and the ‘RRR Benefit Ratio’ indices
- The Recycled content
- The maximum content of hazardous substances in the product (or its components)
- The restriction of the use of potential contaminating materials in the components that could interfere with their reuse/recycling/recovery.

Note that declarative and threshold requirements can coexist. The declarative requirements can be useful to communicate the effective targets that have been achieved by the manufacturer. Furthermore, the adoption of declarative requirements could be preliminary to the setting of threshold requirements.

Potential declarative and thresholds requirements on the ‘post-consumer’ recycled content have been identified concerning plastics. However requirements concerning additional materials could be set for other product categories. Requirements concerning the overall recycled content of the product should instead be avoided. Such requirements, in fact, merge information concerning different materials and they risk generating confusion and being ineffective in term of promotion of the recycling of materials.

Potential requirements concerning hazardous substances have been identified as follows:

- The disassembly of key components (those containing the hazardous substances);
- The declaration of the hazardous substances contained in the product (or in some specific ‘key component’);
- The maximum content of hazardous substances in the product (or some components).

Requirements about the use of hazardous substances could involve hazardous substances regulated by the RoHS Directive or the REACH Regulation, and also other potential hazardous substances not regulated (e.g. flame retardants classified with some risk phrases).

It is important to highlight that some potential Ecodesign requirements here discussed could potentially lead to design measures that worsen the product's overall environmental life cycle performance. For example, the reuse of some EuP's components could cause higher energy consumption during the use phase. A life cycle check is therefore necessary preliminary to the setting of some of the requirements[119] to avoid potential "shifting-of-burdens".

[119] A life cycle check is for example needed for requirements concerning: the thresholds of RRR indices, the thresholds of RRR Benefit indices and the limits of the use of hazardous substances.

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Annex 1: Values of the Recyclability index M_R for various materials

Figure A1.1: Index MR calculated for some metals[120]

SALIENT U.S. RECYCLING STATISTICS FOR SELECTED METALS										
	Quantity of metal (metric tons)					Value of metal (thousands $)				
Year	Recycled from new scrap	Recycled from old scrap	Recycled	Apparent supply	Percentage recycled	Recycled from new scrap	Recycled from old scrap	Recycled	Apparent supply	Index 'M_R'
Aluminum:										
1998	1,950,000	1,500,000	3,440,000	9,040,000	38.0	2,810,000	2,160,000	4,970,000	13,100,000	1.00
1999	2,200,000	1,550,000	3,750,000	9,940,000	38.0	3,180,000	2,240,000	5,420,000	14,400,000	1.00
2000	2,080,000	1,370,000	3,450,000	9,610,000	36.0	3,420,000	2,260,000	5,670,000	15,800,000	1.00
2001	1,770,000	1,210,000	2,980,000	8,000,000	37.0	2,680,000	1,840,000	4,530,000	12,100,000	1.01
2002	1,750,000	1,170,000	2,930,000	8,060,000	36.0	2,510,000	1,680,000	4,190,000	11,500,000	1.00
2003	1,750,000	1,070,000	2,820,000	7,880,000	36.0	2,620,000	1,610,000	4,230,000	11,800,000	1.00
2004	1,870,000	1,160,000	3,030,000	8,460,000	36.0	3,640,000	2,140,000	5,600,000	15,700,000	0.99
2005	1,930,000	1,060,000	2,990,000	8,390,000	36.0	3,870,000	2,140,000	6,000,000	16,800,000	1.00
2006	2,310,000	1,200,000	3,510,000	8,160,000	43.0	6,180,000	3,200,000	9,380,000	21,800,000	1.00
2007	2,250,000	1,600,000	3,850,000	8,660,000	45.0	6,070,000	4,320,000	10,400,000	23,300,000	1.01
Chromium:										
1998	NA	NA	105,000	331,000	19.8	NA	NA	94,400	478,000	0.53
1999	NA	NA	118,000	558,000	21.2	NA	NA	85,500	367,000	1.13
2000	NA	NA	139,000	589,000	23.6	NA	NA	98,600	587,000	0.65
2001	NA	NA	122,000	332,000	37.0	NA	NA	70,800	160,000	1.37
2002	NA	NA	139,000	482,000	29.0	NA	NA	75,700	298,000	0.84
2003	NA	NA	129,000	468,000	27.0	NA	NA	99,200	391,000	0.89
2004	NA	NA	168,000	555,000	30.0	NA	NA	207,000	681,000	1.01
2005	NA	NA	124,000	511,000	24.0	NA	NA	162,000	717,000	0.91
2006	NA	NA	235,000	645,000	36.0	NA	NA	128,000	811,000	0.33
2007	NA	NA	162,000	493,000	33.0	NA	NA	297,000	1,090,000	0.77
Copper:										
1998	942,000	466,000	1,410,000	3,950,000	35.6	1,630,000	808,000	2,440,000	6,850,000	1.00
1999	950,000	381,000	1,330,000	4,080,000	32.7	1,590,000	638,000	2,230,000	6,820,000	1.00
2000	952,000	363,000	1,310,000	4,060,000	32.4	1,850,000	705,000	2,550,000	7,890,000	1.00
2001	833,000	316,000	1,150,000	3,340,000	34.5	1,410,000	535,000	1,950,000	5,650,000	1.00
2002	842,000	207,000	1,050,000	3,450,000	30.4	1,410,000	346,000	1,750,000	5,770,000	1.00
2003	738,000	206,000	944,000	3,170,000	29.8	1,390,000	387,000	1,770,000	5,950,000	1.00
2004	774,000	191,000	965,000	3,330,000	28.9	2,290,000	565,000	2,850,000	9,830,000	1.00
2005	769,000	182,000	951,000	3,170,000	30.0	2,940,000	698,000	3,640,000	12,100,000	1.00
2006	819,000	150,000	968,000	3,000,000	32.3	5,680,000	1,040,000	6,720,000	20,800,000	1.00
2007	768,000	157,000	925,000	3,040,000	30.5	5,550,000	1,090,000	6,690,000	22,000,000	1.00
Iron and steel:										
1998	NA	NA	73,000,000	133,000,000	55.0	NA	NA	7,910,000	17,300,000	0.69
1999	NA	NA	71,000,000	130,000,000	54.0	NA	NA	6,680,000	12,300,000	0.99
2000	NA	NA	74,000,000	134,000,000	55.0	NA	NA	7,100,000	12,800,000	1.01
2001	NA	NA	71,000,000	119,000,000	60.0	NA	NA	5,320,000	8,880,000	1.01
2002	NA	NA	69,000,000	119,000,000	58.0	NA	NA	6,390,000	10,200,000	1.22
2003	NA	NA	61,300,000	117,000,000	52.0	NA	NA	10,500,000	25,000,000	0.66
2004	NA	NA	66,500,000	132,000,000	51.0	NA	NA	13,400,000	24,900,000	1.15
2005	NA	NA	65,400,000	122,000,000	54.0	NA	NA	12,600,000	21,900,000	1.17
2006	NA	NA	65,600,000	136,000,000	48.0	NA	NA	18,500,000	36,100,000	1.13
2007	NA	NA	65,000,000	123,000,000	53.0	NA	NA	16,400,000	29,200,000	1.14

[120] Economic and mass values are derived from the US Geological Survey. Minerals Yearbook, Recycling-Metals 1998–2007 (website: http://minerals.usgs.gov/minerals/pubs/commodity/recycle/). Note: NA=Not Available

Figure A1.2 (continued): Index M_R calculated for some metals

	Quantity of metal (metric tons)					Value of metal (thousands $)				
Year	Recycled from new scrap	Recycled from old scrap	Recycled	Apparent supply	Percentage recycled	Recycled from new scrap	Recycled from old scrap	Recycled	Apparent supply	Index 'M_R'
Lead:										
1998	45,800	1,050,000	1,100,000	1,740,000	63.1	45,700	1,050,000	1,100,000	1,740,000	1.00
1999	42,700	1,050,000	1,090,000	1,790,000	60.9	41,200	1,010,000	1,050,000	1,730,000	0.99
2000	35,400	1,080,000	1,120,000	1,790,000	62.6	34,000	1,040,000	1,080,000	1,720,000	1.01
2001	47,300	1,050,000	1,100,000	1,700,000	65.0	45,500	1,010,000	1,060,000	1,640,000	1.00
2002	34,800	1,070,000	1,100,000	1,540,000	71.4	33,400	1,030,000	1,060,000	1,480,000	1.01
2003	33,900	1,100,000	1,140,000	1,430,000	79.7	32,700	1,060,000	1,100,000	1,380,000	1.00
2004	12,900	1,100,000	1,110,000	1,440,000	83.7	15,600	1,360,000	1,350,000	1,750,000	1.00
2005	15,700	1,130,000	1,140,000	1,540,000	74.5	21,100	1,520,000	1,540,000	2,070,000	1.02
2006	13,500	1,140,000	1,150,000	1,570,000	73.1	23,000	1,940,000	1,960,000	2,680,000	0.99
2007	24,100	1,160,000	1,180,000	1,480,000	79.6	65,700	3,150,000	3,220,000	4,050,000	0.99
Magnesium:										
1998	44,600	31,800	76,400	230,000	33.0	155,000	111,000	266,000	801,000	1.00
1999	55,400	33,900	87,300	232,000	38.0	182,000	116,000	298,000	793,000	1.00
2000	52,200	30,100	82,300	209,000	39.0	158,000	90,800	248,000	630,000	1.00
2001	38,600	27,200	65,800	162,000	41.0	106,000	75,000	181,000	446,000	1.00
2002	47,100	26,400	73,600	162,000	45.0	126,000	70,500	196,000	432,000	1.00
2003	44,700	25,100	69,800	152,000	46.0	107,000	60,200	168,000	366,000	1.00
2004	51,600	20,500	72,100	181,000	40.0	167,000	66,400	234,000	586,000	1.00
2005	53,400	19,400	72,800	167,000	44.0	172,000	62,500	234,000	538,000	1.00
2006	56,000	19,800	75,800	159,000	48.0	143,000	50,600	194,000	406,000	1.00
2007	60,300	23,800	84,000	161,000	52.0	228,000	90,200	319,000	611,000	1.00
Nickel:										
1998	NA	NA	63,300	186,000	34.0	NA	NA	293,000	863,000	1.00
1999	NA	NA	71,000	211,000	33.6	NA	NA	427,000	1,270,000	1.00
2000	NA	NA	84,000	231,000	36.4	NA	NA	725,000	1,990,000	1.00
2001	NA	NA	101,000	230,000	44.0	NA	NA	600,000	1,370,000	1.00
2002	NA	NA	99,800	221,000	45.0	NA	NA	676,000	1,500,000	1.00
2003	NA	NA	93,400	211,000	44.0	NA	NA	899,000	2,030,000	1.00
2004	NA	NA	83,300	212,000	39.3	NA	NA	1,150,000	2,930,000	1.00
2005	NA	NA	77,300	214,000	36.0	NA	NA	1,140,000	3,150,000	1.00
2006	NA	NA	108,000	252,000	43.0	NA	NA	2,620,000	6,100,000	1.00
2007	NA	NA	93,700	208,000	45.0	NA	NA	3,490,000	7,730,000	1.00
Tin:										
1998	8,440	7,710	16,100	54,600	30.0	69,400	63,400	133,000	449,000	1.01
1999	8,650	7,700	16,300	57,200	28.0	69,800	62,100	132,000	462,000	1.00
2000	8,450	6,600	15,100	52,100	29.0	68,800	53,700	122,000	424,000	0.99
2001	7,190	6,700	13,900	50,600	27.0	49,800	46,500	96,300	351,000	1.00
2002	3,590	6,410	10,000	51,200	20.0	23,100	41,200	64,200	329,000	1.00
2003	2,460	5,420	7,880	40,900	19.0	NA	NA	NA	NA	-
2004	3,590	4,850	8,440	52,600	16.0	44,000	59,400	103,000	645,000	0.99
2005	2,280	11,800	14,000	46,500	30.0	24,300	125,000	150,000	495,000	1.01
2006	2,340	11,600	13,900	55,500	25.0	21,700	107,000	129,000	514,000	1.00
2007	2,860	11,900	14,800	44,200	34.0	56,700	236,000	293,000	876,000	1.00
Zinc:										
1998	344,000	82,400	427,000	1,580,000	27.0	352,000	84,400	437,000	1,620,000	1.00
1999	321,000	85,100	406,000	1,610,000	25.2	345,000	91,600	437,000	1,730,000	1.00
2000	369,000	66,900	436,000	1,610,000	27.1	454,000	85,600	540,000	2,060,000	0.96
2001	316,000	52,100	368,000	1,400,000	16.3	306,000	53,800	360,000	1,360,000	1.01
2002	319,000	47,300	366,000	1,430,000	25.6	272,000	40,300	312,000	1,220,000	1.00
2003	295,000	50,300	345,000	1,340,000	25.8	264,000	45,100	309,000	1,200,000	1.00
2004	302,000	47,100	349,000	1,400,000	24.9	421,000	65,600	486,000	1,950,000	1.00
2005	302,000	43,100	345,000	1,170,000	29.5	446,000	63,700	510,000	1,730,000	1.00
2006	294,000	47,800	341,000	1,390,000	24.5	1,030,000	167,000	1,190,000	4,870,000	0.99
2007	207,000	30,100	237,000	1,170,000	20.0	705,000	102,000	807,000	3,980,000	1.00

Table A1.1 Index M_R calculated for some materials

	Average V_m (*)	Average V_r (*)	Average V_p (*)	M_R index
Aluminium	1.59	0.65	1.45	0.91
Copper	1.77	0.9	1.67	0.94
Zinc	1.2	0.9	1.32	1.10
Gold	9653.23	9213.23	9653.23	1.00
Silver	166.55	155	166.55	1.00
Nickel	7.84	5.72	7.84	1.00
Steel	0.29	0.09	0.29	1.00
Tin	5.74	4.07	-	-
PET	1.68	0.14	1.15	0.68
Paper	0.9	0.08	0.14	0.16
Glass	0.38	0.02	-	-
PE-HD	1.1	0.24	0.93	0.85
PP	0.59	0.21	-	-
Stainless steel	1.94	0.47	-	-

notes:
(*) values from [Villalba et al, 2002]
Vm : value of material of first-production/virgin ($/kg)
Vr : value of material post-recycled ($/kg)
Vp : value of material post-use ($/kg)

Table A1.2 Index M_R calculated for some polymers and paper pulp

	1991		**1992**		**1993**		**1994**		Average M_R
	Prices (*)	M_R	Prices (*)	M_R	Prices (*)	M_R	Prices (*)	M_R	
PET		0.73		0.74		0.79		0.68	*0.74*
Recycle	0.48		0.49		0.52		0.52		
Virgin	0.66		0.66		0.66		0.76		
PE-HD		1.00		0.94		0.83		0.84	*0.90*
Recycle	0.38		0.34		0.3		0.42		
Virgin	0.38		0.36		0.36		0.5		
PE-LD		-		0.72		0.78		0.64	*0.71*
Recycle	-		0.28		0.29		0.34		
Virgin	0.3		0.39		0.37		0.53		
PS		0.91		0.94		0.90		0.68	*0.86*
Recycle	0.4		0.44		0.44		0.44		
Virgin	0.44		0.47		0.49		0.65		
Paper pulp		-		-		-		0.17	*0.17*
Recycle	-		-		-		0.07		
Virgin	-		-		-		0.41		

Note: (US$ per pounds) from [Rader and Stocker, 1995]

Table A1.3 Index M_R calculated for some polymers

	Pricing range (Virgin)	Pricing range (recycled)	Average M_R
	US$ cent per pound		
ABS	103 - 168	60 - 78	0.84
Polycarbonate	163 - 250	69 - 81	0.77
PE-HD	75 - 98	32 - 55	0.75
PE-LD	88 - 101	21 - 39	0.65
PET	68 - 79	32 - 66	0.76
PP	93 - 139	48 - 62	0.81
PS	84 - 134	44 - 80	0.82
PVC	66 - 87	30 - 38	0.76

Note : data from Plasticnews website (http://plasticsnews.com) and referred to August 2010

Annex 2: Life-cycle data of some materials

Table A2.1 Primary Energy (PEC) consumption and Global Warming Potential (GWP) concerning the primary and secondary production of some materials

	Primary production			Secondary production		
	PEC [MJ/kg]	GWP [kgCO2eq/kg]	notes/ reference	PEC [MJ/kg]	GWP [kgCO2eq/kg]	notes/ reference
Aluminum	173.1	9.7	Primary aluminum in ingots (Average Europe) [EAA, 2008]	7.7	0.5	Aluminum recycling (average Europe) [EAA, 2008]
	183	11	Aluminum ingot [GABI]	8.2	0.4	Aluminum ingot secondary [GABI]
Copper	68.9	4.1	Copper mix (from electrolysis)[GaBi]	6.3	0.4	Average secondary copper from scrass [BIR, 2008]
	33	3.2	Primary copper (from 3% Cu ores) [BIR, 2008]		0.1	Average production of secondary copper (USA) [Giurco et Petrie., 2007]
		7.3	Average production of primary copper (USA) [Giurco et Petrie., 2007]	7.3		Average data for secondary copper [Norgate, 2004]
Lead	26.9	1.8	Lead (primary production) [ELCD, 2010]	10.0	0.5	Estimation for secondary lead production [Hammond and Jones, 2008]
	20.0	2.1	Primary Lead (from blast furnace) [BIR, 2008]	9.1		Average data for secondary lead [Norgate, 2004]
	32.0	3.2	Primary Lead (from imperial smelting) [BIR, 2008]	9.0		[Graedel and Howard-Grenville, 2005]
	49	2.6	Estimation for primary lead production [Hammond and Jones, 2008]			
	39.0		[Graedel and Howard-Grenville, 2005]			
Magnesium	284	42	Average value for magnesium in car industry in Japan [Hakamada et al., 2007]	11.4	1.7	Average value for magnesium in car industry in Japan [Hakamada et al., 2007]
		19	Average value for magnesium in car industry in USA [Tharumarajah and Koltun, 2007]		3.6	Average value for magnesium in car industry in USA [Tharumarajah and Koltun, 2007]
Nickel	159.0		Primary nickel production [Rydh and Karlstrom, 2002]	40.0		Secondary nickel from Ni/Cd batteries recycling [Rydh and Karlstrom, 2002]
	518	31.7	Primary production of Ferronickel (32% Ni) [Nickel Institute, 2003]	1.9	0.22	Theoretical secondary production from scraps [BIR, 2008]
	455	28	Primary production of Nickel oxide (77% Ni) [Nickel Institute, 2003]	15.4		Average data for secondary Nickel [Norgate, 2004]
	239	14.7	Primary production of Nickel Class I (99.3% Ni) [Nickel Institute, 2003]			
Platinum	218,500		Platinum primary (estimation from [J. van Rooijen, 2006] and [Pehnt, 2001])	43,700		Platinum secondary (estimation from [J. van Rooijen, 2006] and [Pehnt, 2001])
Steel	33.2	3.2	Steel sheet [GaBi]	12.5	1.2	Steel sheet secondary [GaBi]
	35.3	2.75	General steel product [Hammond and Jones, 2008]	9.5	0.43	General recycled steel product [Hammond and Jones, 2008]
Tin	33.3	3.2	Tin plate [GaBi]	14.2	1.3	Secondary tin plate (including de-tinning) [GaBi]
Titanium	361	35.7	Titanium (from Becher and Kroll process) [Norgate et al., 2007]			
	317	31	Titanium (from Becher and Kroll process) [Norgate et al., 2007]			
	430		[Graedel and Howard-Grenville, 2005]	140		[Graedel and Howard-Grenville, 2005]
Zinc	49.3	3.2	High grade Zinc, primary production at plant [ELCD, 2010]	9	0.5	Average values for secondary zinc production [Hammond and Jones, 2008]
	61		[Graedel and Howard-Grenville, 2005]	24		[Graedel and Howard-Grenville, 2005]
	72	3.9	Average values for zinc production [Hammond and Jones, 2008]	13.7		Average data for secondary zinc [Norgate, 2004]

Table A2.1 Primary Energy (PEC) consumption and Global Warming Potential (GWP) concerning primary and secondary production of some materials (continue)

	Primary production			Secondary production		
	PEC [MJ/kg]	GWP [kgCO2eq/kg]	notes/ reference	PE [MJ/kg]	GWP [kgCO2eq/kg]	notes/ reference
Brass	80	4.4	estimation for brass production [Hammond and Jones, 2008]	20	1.1	Estimation for brass production [Hammond and Jones, 2008]
Cadmium	70.0		Primary cadmium production [Rydh and Karlstrom, 2002]	38.0		Secondary cadmium from Ni/Cd batteries recycling [Rydh and Karlstrom, 2002]
Cardboard	30.4	0.68	Corrugated board, Virgin fibers [BUWAL]	10.1	0.56	Corrugated board from recycled fibers [BUWAL]
Glass	12.7	0.8	Glass packagin white [BUWAL]		0.5	Recycled glass bottle in UK [British glass, 2003]
PE-HD	70.8	1.9	Polyethylene High Density granulate [ELCD]	8.7	0.6	Recycled PE-HD (average in USA) [Franklin, 2010]
Paper	62.8	1.0	Kraft Paper bleached [BUWAL]	15.3	0.4	Paper recycling with deinking (in Europe) [BUWAL]
				13.2	0.6	Paper recycling without deinking (in Europe) [BUWAL]
PE-LD	72.2	2.1	Polyethylene Low Density granulate [ELCD, 2010]	15.0	0.9	Recycled PE-LD film (in USA) [Franklin, 2004]
PET	76.5	3.4	Polyethylene terephthalate granulate (bottle grade) [ELCD, 2010]	11.4	0.8	Recycled PET flake (average in USA) [Franklin, 2010]
				16.8	1.1	Recycled PET pellets (average in USA) [Franklin, 2010]
PP	86.6	2.3	Polypropylene granulate [ELCD, 2010]	24.9	1.1	Production of PP components (from 90% recycled PP) [Ardente et al., 2009]
	100.9	3.3	Polypropylene film [PlasticEurope]			
PS	82.0	4.5	Polystyrene expandable granulate [ELCD, 2010]	16.1	1.1	Recycled PS-E (thermal shrinking in Japan) [Noguchi et al., 1998]
				12.8	0.79	Recycled PS-E (with limonene oil in Japan) [Noguchi et al., 1998]
Stainless steel	80.0	5.3	Primary stainless steel [Johnson et al, 2008]	20.5	1.6	Secondary form 100% austenitic stainless steel scraps [Johnson et al, 2008]

Table A2.2 Primary Energy (PEC) consumption and Global Warming Potential (GWP) concerning the primary and secondary production of some materials (selection of representative data derived from Table A2.1)

	Primary production			Secondary production		
	[MJ/kg]	[kgCO2eq./kg]	notes/ reference	[MJ/kg]	[kgCO2eq./kg]	notes/ reference
Aluminum	173.1	9.7	Data from EEA.	7.7	0.5	Data from EEA.
Brass	80.0	4.4	Data from Hammond and Jones.	20.0	1.1	Data from Hammond and Jones.
Cadmium	70.0		Data from Rydh and Karlstrom.	38.0		Data from Rydh and Karlstrom.
Cardboard	30.4	0.7	Data from BUWAL	10.1	0.6	Data from BUWAL
Copper	33.0	3.2	From BIR average data	6.3	0.4	From BIR average data
Glass	12.7	0.8	Data from US LCI		0.5	Data from British glass
PE-HD	70.8	1.9	Data from [ELCD, 2010]	8.7	0.6	Data from Franklin
Lead	26.9	1.8	Data from [ELCD, 2010]	10.0	0.5	Data from Hammond and Jones
Magnesium	284.0	42.0	Data from Hakamada	11.4	1.7	Data from Hakamada
Nickel	404.0	24.8	Average data from the Nickel Institute	27.7	0.0	Average data from Norgate and 'Rydh and Karlstrom'
Paper	62.8	1.0	Data from BUWAL	14.3	0.5	Average from data of BUWAL
PE-LD	72.2	2.1	Data from [ELCD, 2010]	15.0	0.9	Data from Franklin
PET	76.5	3.4	Data from [ELCD, 2010]	14.1	1.0	Average data from Franklin
PP	86.6	2.3	Data from [ELCD, 2010]	24.9	1.1	Data from Ardente et al.
Platinum	218,500	0	Estimation from van Rooijen and Pehn	43,700	0	Estimation from van Rooijen and Pehn
PS	82.0	4.5	Data from [ELCD, 2010]	14.5	1.0	Average from data of Noguchi
Steel	34.3	3.0	Average data from GaBi and Hammond and Jones.	11.0	0.8	Average data from GaBi and Hammond and Jones.
Stainless steel	80.0	5.3	Data from Johnson	20.5	1.6	Data from Johnson
Tin	33.3	3.2	Data from GaBi	14.2	1.3	Data from GaBi
Titanium	430.0		Data from Graedel and Howard-Grenville.	140.0		Data from Graedel and Howard-Grenville.
Zinc	49.3	3.2	Data from [ELCD, 2010]	9.0	0.5	Data from Hammond and Jones.

Table A2.3 Materials without available LCA data concerning their primary or secondary production[121]

Material	Notes	PE [MJ/kg]	GWP [kg CO_2/kg]
ANTIMONY	Although antimony (Sb) is usually described as a metal, it possesses mixed metallic and non-metallic characteristics and is more properly described as a semimetal or metalloid. Nearly all antimony is consumed in one of the following four forms [Carlin, 2000]: antimony trioxide, which is used mostly for flame retardants; antimonial lead alloys, which are used mostly in lead-acid (LA) batteries; refined antimony metal, which is used in a variety of metallic products; and sodium antimonate, which is used for the clarification of specialty glasses. Flame retardants were the primary end-use for antimony and accounted for about 50 percent of all consumption in 2000 [Carlin, 2000]. Flame retardants use antimony tri-oxide as an agent, along with bromine, to slow the spread of fire in applications such as automotive and aircraft seat covers, children's clothing, and toys. Virtually no antimony is recycled from flame retardant uses. Most secondary antimony is instead recovered by recycling used batteries [Carlin, 2000]. Almost no antimony is recycled from other old scraps [Carlin, 2000]. Estimated value of Energy Consumption for the concentration & refining is: 13.4 MJ/kg [Valero and Botero, 2002].		
BARYTE	Barite is a mineral used as a weighting agent in gas and oil-well drilling fluids. It is also used as a filler, extender, or weighting agent in products such as paints, plastics, and rubber. Some specific applications include its use in automobile brake and clutch pads and automobile paint primer for metal protection. Ultrapure barite consumed as liquid is used as a contrast medium in medical x-ray examinations. Recycling of barite is insignificant [USGS, 2010].		
BORON	Boron (B) minerals and chemicals were principally consumed for the production of glass and ceramics, soaps, detergents, and bleaches, agriculture and glazes. According to the US geological survey, Boron recycling is insignificant [USGS, 2010].		
BERYLLIUM	About 75 % of USA beryllium (Be) consumption is in the form of beryllium-copper alloys that are used mostly in electrical and electronic components [Cunningham, 2000]. Little beryllium, however, is recovered from used products (old scrap) owing to their small size, difficulty in separation, and the low beryllium content in the alloys; beryllium-copper alloys contain about 2 percent beryllium. Also, little beryllium metal old scrap is recycled; much of the metal is contained in nuclear reactors and nuclear weapons, which are difficult to recycle and may have been contaminated. Most of the recycling of beryllium-copper alloy old scrap products is undertaken to reclaim the copper value [Cunningham, 2000]. Estimated value of Energy Consumption for the concentration & refining is: 457.2 MJ/kg [Valero and Botero, 2002].		
CHROMIUM	The major end use of chromium (Cr) is in stainless steel, and this is the major form in which chromium is recycled. Chromites ore is smelted to make ferrochromium, a chromium-iron alloy that results from the removal of oxygen from chromites. Ferrochromium is then added to iron at steel-producing plants to make the iron-chromium alloy stainless steel. Stainless steel scrap can substitute for ferrochromium as a source of chromium. Since no chromium is recycled within the chromium industry, but directly to the foundries of the stainless steel industry, no LCA data about production of secondary chromium were available [Althaus and Classen, 2005].	90.3 [122]	7.7
COBALT	Cobalt (Co) is a metal used in numerous diverse commercial, industrial, and military applications. On a global basis, the leading use of cobalt is in rechargeable battery electrodes. Super-alloys, which are used to make parts for gas turbine engines, are another major use for cobalt. Cobalt is also used to make airbags in automobiles; catalysts for the petroleum and chemical industries; cemented carbides; corrosion- and wear-resistant alloys; drying agents for paints, varnishes, and inks; dyes and pigments; ground coats for porcelain enamels; high-speed steels; magnetic recording media; magnets [USGS, 2010]. In 2009, cobalt contained in purchased scrap represented an estimated 24% of USA cobalt reported consumption [USGS, 2010]. Some studies of LCA regarded the recycled of Cobalt together with other resources (mostly Nickel and Lithium) from old batteries, but no LCA data were available about PE and GWP of secondary cobalt production.		

[121] When available, data about the primary production have been inserted.
[122] Ferrocrome [GaBi]

Table A2.3 Materials without available LCA data concerning their primary or secondary production [123] **(continue)**

Material	Notes	PE [MJ/kg]	GWP [kg CO_2/kg]
DIATOMITE	Diatomite is a sedimentary rock frequently used in filter aids, cement additives, absorbents, fillers, insulation, and for other applications, including specialized pharmaceutical and biomedical uses. No recycling of Diatomite is detected [USGS, 2010].		
FELDSPAR	Feldspar is used for glassmaking, for most ceramic and filler applications. Currently recycling of feldspar is not detected [USGC, 2010].		
FLUORSPAR	Fluorspar is used for the production of hydrofluoric acid (HF). This acid is used for the manufacture of fluorine-bearing chemicals and is also a key ingredient in the processing of aluminium and uranium. A minor amount of fluorspar is used in steelmaking, in iron and steel casting, primary aluminium production, glass manufacture, welding rod coatings, cement production, and other uses or products. Small quantities of fluorspar are recycled primarily from uranium enrichment, but also from petroleum alkylation and stainless steel pickling [USGS, 2010]		
GALLIUM	Gallium arsenide (GaAs) and gallium nitride (GaN) electronic components represented almost the totality of gallium consumption in USA. Gallium consumed was mainly used in integrated circuits (ICs), optoelectronic devices, which include laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells. At the current situation no old scraps are recycled. Substantial quantities of new scrap generated in the manufacture of GaAs-base devices were reprocessed [USGS, 2010].		
GERMANIUM	The production of germanium (Ge) consists of generation of germanium concentrate followed by actual production of germanium and germanium oxide. The value of germanium is a driving force for its recycling. Optical fibres and fibber optic detectors, which are the major end uses, accounted for about 50 % of the end-use market of germanium in the USA in 2000 [Jorgenson, 2000]. The amount of germanium recycled from finished fibre optic components (old scrap), however, is very small because this source has not yet been fully developed. De-manufacturing, or the disassembly of obsolete products, is another method for recycling electronic equipment, which often contains minute amounts of germanium. Components, which range from laptops to mainframes, can be shredded, and the materials, separated, although the low germanium content precludes its economic recovery [Jorgenson, 2000]. Estimated value of Energy Consumption for the refining is: 2215.5 MJ/kg [Valero and Botero, 2002].		
GYPSUM	Gypsum is one of the most widely used minerals in the world. Mostly gypsum is used to make wallboard for buildings. [USGS, 2010]. Gypsum scraps is recycled from wallboard manufacturing, wallboard installation, and building demolition is recycled. The recycled gypsum is used primarily for agricultural purposes and feedstock for the manufacture of new wallboard [USGS, 2010]. Although several LCA study concerned gypsum products, no LCA were available concerning secondary gypsum production. Generally gypsum scraps are re-inserted into the manufacturing process, and data about environmental impacts are presented aggregated.	1.8 [124]	0.1
GRAPHITE	The major uses of natural graphite are refractory applications, foundry operations, brake linings, lubricants. Graphite is recycled from refractory brick and linings, alumina-graphite refractories for continuous metal castings, magnesia-graphite refractory brick for basic oxygen and electric arc furnaces, and insulation brick. The market for recycled refractory graphite material is growing with material being recycled into products such as brake linings and thermal insulation [USGS, 2010]. Recovering high-quality flake graphite from steelmaking is technically feasible, but not practiced at the present time. The abundance of graphite in the world market inhibits increased recycling efforts [USGS, 2010].		
INDIUM	Indium (In) is produced mainly from residues generated during zinc ore processing. Production of indium tin oxide (ITO) continued to be the leading end use of indium and. ITO thin-film coatings were primarily used for electrically conductive purposes in a variety of flat-panel devices (as liquid crystal displays LCDs). Other end uses included solders and alloys, compounds, electrical components and semiconductors [USGS, 2010]. Indium is most commonly recovered from ITO. Some LCD manufacturers have developed a process to reclaim indium directly from scrap LCD panels. Few quantities of indium are recovered but recently indium recovery from tailings improved thanks also to the high prices of the indium [USGS, 2010].		

[123] When available, data about the primary production have been inserted.
[124] Anhydrite (CaSO4) [ELCD, 2010]

Table A2.3 Materials without available LCA data concerning their primary or secondary production [125] **(continue)**

Material	Notes	PE [MJ/kg]	GWP [kg CO_2/kg]
LIMESTONE	Limestone (or crushed stone) is largely used as construction aggregates, mostly for road construction and maintenance, for cement manufacturing, for lime manufacturing, for agricultural uses. Road surfaces made of asphalt and crushed stone and, to a lesser extent, cement concrete surface layers and structures, are generally recycled on a limited but increasing basis [USGS, 2010]. LCA data of secondary limestone was not available. Some studies referred to limestone recycling, but LCA data are not disaggregated from the overall analysis.	0.27 [126]	0.01
LITHIUM	Although lithium (Li) markets vary by location, global end-use markets are mainly: ceramics and glass, batteries, lubricating greases, air treatment, continuous casting, primary aluminium production. Lithium use in batteries expanded significantly in recent years because rechargeable lithium batteries were being used increasingly in portable electronic devices and electrical tools. Recycling of lithium is not significant, but increasing through the recycling of lithium batteries [USGS, 2010]. Although several studies have been done concerning the recycling of lithium batteries, no LCA data were available concerning the PEC and GWP of secondary lithium production.		
MANGANESE	Manganese (Mn) is mostly used as an alloying agent in alloys in which it has a minor component (ferromanganese is used for alloying steel while manganese is used for alloying aluminium or for direct use). Manganese is recycled mostly within scrap of iron and steel (where it has an average content of 0.7%) [USGS, 1998]. A small amount is recycled within aluminium used beverage cans. Very little manganese was recycled from materials being recovered specifically for their manganese content.	Ferro-Mn 129 [127] SiMn 170	Ferro-Mn 8.4 SiMn 11
MOLYBDENUM	Molybdenum (Mo) is a refractory metallic element used principally as an alloying agent in steel, cast iron, and super-alloys to enhance hardenability, strength, toughness, and wear and corrosion resistance. Molybdenum is recycled as a component of ferrous scrap, which comprises home, new, and old scrap [Blossom, 1998]. The molybdenum component is identified in scraps, but in most cases, the scrap is selected for other elements that it contains. Alloy and stainless steel are major sources of molybdenum-bearing scrap. Although molybdenum is not recovered separately from scrap steel and super-alloys that contain it, recycling of these alloys is significant [Blossom, 1998].		
NIOBIUM	Niobium (Nb) is a ductile refractory metal that is used mostly as an alloying element in steels to improve corrosion-resistance and strength characteristics. Because of its refractory nature, appreciable amounts of niobium are used in cobalt-, iron-, and nickel-base super-alloys [Cunningham, 1998]. Although niobium is not recovered from the scrap steel and super-alloys that contain it, recycling of these scrap materials is significant, and columbium content, where applicable, can be reused [Cunningham, 1998]. As reported by Hartikainen et al., 2004, the usage of chemicals in niobium processing are unknown and niobium processing companies consider also their energy usage as proprietary information. Authors estimated that the impacts for the production of 1 kg of NbTi-ingot amount to: Net energy consumption of 376 MJ; CO2 emission of 20.4 kgCO2.		
PERLITE	Perlite is a volcanic amorphous glass. The main end-uses of perlite are: construction products, fillers, horticultural aggregate and filter aid. No recycling has been developed [USGS, 2010].		
RARE EARTHS	The rare earths are a relatively abundant group of 17 elements composed of scandium, yttrium, and the lanthanides. They are typically soft, malleable, and ductile and usually reactive, especially at elevated temperatures or when finely divided. In 2008 the distribution of rare earths by end use in USA, in decreasing order, was as follows: metallurgical applications and alloys, electronics, chemical catalysts, rare-earth phosphors for computer monitors, lighting, radar, televisions, and x-ray-intensifying film, automotive catalytic converters, glass polishing and ceramics, permanent magnets, and petroleum refining catalysts [USGS, 2010]. Small quantities of rare earth are recycled, mostly concerning permanent magnet scraps. [USGS, 2010] Some LCA data have been produced concerning rare earths: Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Ne), Gadolinium (Gd), Yttrium (Y)[128]. No LCA data were instead available on secondary resources production.	La: 219.4 Ce: 354.2 Pr: 220.1 Ne: 392 Gd: 2162 Y: 755.9	La: 39.6 Ce: 67.6 Pr: 40.5 Ne: 75.5 Gd: 423.6 Y: 144.9

[125] When available, data about the primary production have been inserted.
[126] Crushed stone from ELCD, 2010
[127] All data from [Cronje, 2004].
[128] All data in the table refer to [Koltun and Tharumarajah, 2010]

Table A2.3 Materials without available LCA data concerning their primary or secondary production [129] (continue)

Material	Notes	PE [MJ/kg]	GWP [kg CO_2/kg]
RHENIUM	Rhenium (Re) is a rare metal, averaging not more than 4 parts per billion in the Earth's crust. Nowhere rhenium is mined as the main product [Lipmann, 2005]. It occurs principally in copper deposits but is only recovered at those mining operations that generate by-product molybdenum sulphide concentrates. Hence, the supply of rhenium is governed by the copper output. Demand for rhenium in the alloying sector relies to a great extent on the use in the aerospace industry. The addition of rhenium increases the alloy's resistance to deformation. The recovery of rhenium from spent reforming bi-metallic catalysts is a mature business [Lipmann, 2005]. As spent catalysts emerge, they are sent for recovery, essentially to recuperate the more valuable platinum. Without an expensive metal like platinum to provide the incentive, the recovery of rhenium from complex alloys or resins is an extremely marginal process [Lipmann, 2005]. However, with the developing shortage of rhenium and the attendant price rise, there is a growing incentive for secondary rhenium. Estimated value of Energy Consumption for the concentration & refining is: 171 MJ/kg [Valero and Botero, 2002].		
TALC	The mineral talc is a hydrous magnesium silicate. Talc is used commercially because of its fragrance retention, purity, softness, and whiteness. Other commercially important properties of talc are its chemical inertness, high dielectric strength, high thermal conductivity, low electrical conductivity, and oil and grease adsorption. Major markets for talc are ceramics, paint, paper, and plastics. Recycling of talc is insignificant [USGS, 2010].		
TANTALUM	The major use for Tantalum (Ta), as tantalum metal powder, is in the production of electronic components. Tantalum was mostly recycled from new scrap that was generated during the manufacture of tantalum-containing electronic equipment and from new and old scrap products of tantalum-containing cemented carbides and super-alloys [Cunningham, 1998b]. The amount of tantalum recycled from finished electronic components (old scrap) is very small because this source has not yet been fully developed. New scrap materials reclaimed at manufacturing plants that produce tantalum-containing electronic equipment are a major source of tantalum supply and are delivered back to tantalum processors for recycling [Cunningham, 1998b].		
TELLURIUM	Tellurium (Te) major use is as an "alloying additive in steel to improve machining characteristics. It is also used as a minor additive in copper alloys to improve machinability without reducing conductivity; in lead alloys to improve resistance to vibration and fatigue; in cast iron to help control the depth of chill; and in malleable iron as a carbide stabilizer. It is used in the chemical industry as a vulcanizing agent and accelerator in the processing of rubber" [George, 2010]. "There is little or no scrap from which to extract secondary tellurium because the uses of tellurium are nearly all dissipative in nature. Currently, none is recovered in the United States, but a very small amount is recovered from scrapped selenium-tellurium photoreceptors employed in older plain paper copiers in Europe" [George, 2010].		
TUNGSTEN	Tungsten (W) is a metal with a wide range of uses, the largest of which is as tungsten carbide in cemented carbides. The remaining tungsten is consumed to make tungsten heavy alloys for applications requiring high density; electrodes, filaments, wires, and other components for electrical, electronic, heating, lighting, and welding applications; steels, super-alloys, and wear-resistant alloys; and chemicals for various applications [USGS, 2010]. In 2009, the recycled tungsten contained in scrap consumed by processors and end users represented approximately 37% of apparent consumption of tungsten in all forms in USA [USGS, 2010].		
VANADIUM	Vanadium (V), when present in small amounts in certain ferrous alloys, can significantly improve their properties. Vanadium alloys are used by manufacturers of automobiles and machinery. Vanadium is also used together with aluminium to give the required strength in titanium alloys used in jet engines and high-speed airframes [USGS, 2010]. Authors accounted that in USA some tool steel scrap was recycled primarily for its vanadium content, and vanadium was recycled from spent chemical process catalysts, but these two sources together accounted for only a very small percentage of total vanadium consumed [USGS, 2010]. The vanadium content of other recycled steels was lost to slag during processing and was not recovered.		

[129] When available, data about the primary production have been inserted.

European Commission

Joint Research Centre – Institute for Environment and Sustainability
Title: *In-depth analysis of the measurement and verification approaches, identification of the possible gaps and recommendations*
Author(s): F. Ardente, M-A. Wolf, F. Mathieux, D. Pennington

Abstract

The present report develops new methodologies for the measurement and the verification of the following parameters for use in Ecodesign policies:

- Reusability/Recyclability/Recoverability (RRR);
- Recycled content;
- Use of priority resources;
- Use of hazardous substances.

The methodologies are based on the calculation of one (or more) indices for each of the above parameters. The indices can be applied at the design stage.

The indices have a 'modular' structure. This means that they are calculated as product of different sub-indices. The modularity of the indices allows including or excluding some of the sub-indices without compromising the methodology itself. Furthermore, new sub-indices can be added in future, reflecting additional aspects that have not been investigated at this stage. Analogously, some indexes can be modified or removed on the basis of the expected targets of the decision-makers, effectiveness, and other considerations.

Verification procedures have been elaborated for each index and sub-index. The verification is generally based on self-declarations supported by technical documentation available before the product is put into the market and provided on request (e.g. to be checked by a competent body).

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