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Environmental Footprint and Material Efficiency Support for product policy

Analysis of material efficiency requirements of enterprise servers

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Abstract

This study is part of the 'Environmental Footprint and Material Efficiency Support for product policy' project funded by DG Environment (AA 070307/2012/ENV.C1/635340). In June 2013, the preparatory study of enterprise servers was launched with the objective of identifying ways to improve their environmental performance. In early 2014, and in parallel to the preparatory study process, JRC-IES started a study for this product group with the aim to provide scientific support in the analysis of the end of life (EoL) and potential material efficiency requirements. The results of such study are those included in this report and aims to provide: more transparent and clear data about material composition of components included in servers; more exhaustive description about the end of life (EoL) of servers; and a more complete estimate of the benefits of the reuse and recycling of servers, in addition to global warming potential. All these additional information together is used as the basis to formulate new potential resource efficiency requirements for servers.

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Executive Summary

This study is part of the 'Environmental Footprint and Material Efficiency Support for Product Policy' project funded by DG Environment from 2012 until 2015. Material-efficiency criteria for products have become increasingly relevant for EU policy, as reflected in some of the latest communications in which the European Commission has manifested its interest in "moving towards a more circular economy"[1]. In particular, the Commission aims to go beyond its initial objectives (European Commission 2011; European Commission 2014)) and support innovative actions at all stages of the lifecycle of products, from the extraction of raw materials, through material and product design, production, distribution and consumption of goods, repair, remanufacturing and re-use schemes, to waste management and recycling[2]. In an innovative circular economy, nothing is wasted, natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance society's resilience. This report aims to contribute to such efforts by identifying potential material-efficiency measures that can help improve the reuse and recycling of enterprise servers.

This study is one of a series of publications that assess the material efficiency of energy-related products (ErPs). Previous reports in the series have analysed the material efficiency of washing machines, electronic displays, dishwashers, and computers[3]. These products were selected because of their policy relevance at the time, as they were the subject of preparatory and/or technical studies within the scope of the EU's Ecodesign Directive and the EU Ecolabel scheme.

In June 2013, a preparatory study of Ecodesign measures for enterprise servers was launched with the objective of identifying ways to improve their environmental performance. In early 2014, and in parallel with the preparatory study process, the JRC IES undertook a study of this product group with the aim of providing scientific support to the analysis of its material composition, end-of-life (EoL) and potential material-efficiency requirements. In line with an analysis of the literature, this report proposes four potential requirements for servers.

Requirement 1: The reuse of components in servers: this requirement aims to facilitate the entry of servers with reused components into the market by introducing bonus systems (e.g. by reducing the potential threshold for total annual energy consumption). Section 4.6 of this report applies and discusses a method for the assessment of the environmental benefits of reusing server components. Previously calculated indices can be used to establish requirements that promote the reuse of components. Servers with reused components can be environmentally convenient even when their energy efficiency is lower than that of new servers. In order to test the efficacy of this requirement, systems that can trace reused components are needed. Standards could be developed to support the traceability of reused components[4], including existing standards on design for reuse.

Requirement 2: Design for disassembly, reuse and recycling, and recovery: as shown in the environmental assessment (section 4.5), some components of servers generate most of the environmental impact during manufacturing. These components also contain most of the valuable materials of the server, the extraction of which is an economic incentive for recyclers. Hard disk drives (HDDs) and memory cards are generally designed to allow for their ease of extraction, whereas

[1] http://ec.europa.eu/environment/circular-economy/index_en.htm
[2] http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf
[3] Reports can be downloaded from: http://sa.jrc.ec.europa.eu/?page_id=775
[4] For example, standard VDI 2343 - Part 7 "Recycling of electrical and electronic equipment - Re-use" (2014)

further steps are needed for the extraction of the main boards and processors. The requirement is formulated with the aim of improving the accessibility and extractability of these components, in order to facilitate both the reversible disassembly for reuse and the dismantling for recycling.

Requirement 3: Provision of technical information: technical information includes an exploded diagram of the product illustrating the components that need special handling and other targeted components, documentation of the sequence of the disassembly operations, and the availability of firmware to test the functionality of and compatibility between components in the server[5].

Requirement 4: Provision of information concerning critical raw materials: this requirement aims to improve the availability of data on electrical and electronic equipment, by furnishing information about the location and amount of critical raw materials included in enterprise servers, especially in HDDs.

The reasoning behind each of the requirements is extensively reported within this report. The **reuse of components** is debated (**section 3.2.1)** using information collected from some manufacturers and specialised reuse/repair operators**.** The **potential benefits of reusing components in servers** are illustrated in **section 4.6.1**, based on a novel method developed by the JRC IES**.** The **design for disassembly, reuse and recycling** is discussed in **section 4.2**, based on the dismantling and analysis of a series of servers**. Section 4.6.2** estimates the potential benefits of recycling in different end-of-life scenarios, using the REAPro method[6] developed by the JRC IES. The **provision of technical information** is formulated based on findings described in **sections 3.2.2** and **4.2.** The **provision of information concerning critical raw materials** in servers is described in **sections 4.2** and **4.3**, and further discussed in **section 4.5.3.**

The proposed requirements are also built upon measures discussed in the framework of other environmental schemes, such as the US environmental leadership standard and the Code of conduct for energy efficiency in data centres (section 3.4).

During the current analysis, close communication was maintained with the consultants developing the preparatory study on the Ecodesign of enterprise servers (Lot 9)[7]. Some of the results of the present study were provided as input to the ongoing preparatory study, such as the content of critical raw materials in some components of enterprise servers, detailed breakdowns of some components, and potential environmental impacts of the manufacturing of PCBs. This information facilitated the application of the Methodology for the Ecodesign of Energy-related Products (MEErP)[8] and the environmental assessment during the preparatory study. The reports of the preparatory study also include some of the results and the proposals of the present report, with the goal to promote greater resource efficiency at the end-of-life of enterprise servers, thereby improving current reuse and recycling practices, and promoting the move towards a more circular economy in the information and technology sector.

[5] The lack of firmware has been highlighted by reuse and refurbishing companies as one of the main barriers to the reusability of servers.

[6] Resource Efficiency Assessment of Products (REAPro) method. For further details, see Ardente and Mathieux (2014).

[7] "Preparatory study on Enterprise servers" "Preparatory study for implementing measures of the Ecodesign Directive 2009/125/EC: DG ENTR Lot 9 - Enterprise servers and data equipment" (http://www.ecodesign-servers.eu/home)

[8] http://www.meerp.eu/

Acronyms

ADP – Abiotic Depletion Potential
AHWG – Ad-Hoc Working Group for EU Ecolabel
BoM – Bill of materials
CRM – Critical raw materials
CPU – Central processing unit
DG ENTR – Directorate General for Enterprise and Industry
DG ENV – Directorate General for the Environment
EC – European Commission
ECEEE – European Council for an Energy Efficient Economy
EoL – End-of-Life
ErP – Energy-related Product
EU – European Union
EUEB – European Union Ecolabelling Board
FMD - Full Material Declarations
GHS – Globally Harmonized System of Classification and Labelling of Chemicals
GPP – Green public procurement
GWP – Global Warming Potential
HDD – Hard disk drive
ICT - Information and communication technology
ILCD – International Reference Life Cycle Data
IPCC – Intergovernmental Panel on Climate Change
JRC – Joint Research Centre
LCA – Life cycle assessment
MLCC capacitor - Micro Leadframe Chip Carrier capacitor
NGOs – Non-governmental organisations
OEM - original equipment manufacturers
ODD - Optical disk drive
PBDE – Polybrominated diphenyl ethers
PBB – Polybrominated biphenyls
PCB – Printed circuit board
PEF – Product environmental footprint
PGM – Platinum group metals
PSU – Power supply unit
REACH – Registration, Evaluation, Authorisation and Restriction of Chemicals
REAPro – Resource Efficiency Assessment of Products
RoHS – Restriction of Hazardous Substances
SSD – Solid State Drive
SVHC – Substance of Very High Concern
TPM - Third party maintenance
WEEE - Waste of Electrical and Electronic Equipment

1. Introduction

As the implementation of material-efficiency measures in product policies is progressively gaining more importance, it is important to identify for which products such implementation is necessary, and will have the most impact and thus provide the greatest benefits in environmental and economic terms. In line with this objective, enterprise servers are considered to be a priority product given the fact that the preparatory study for the Ecodesign regulation of servers is currently (at the time the present study was developed) being carried out. In fact, the present study was run in parallel to Lot 9 of the preparatory study, with the aim of supporting and complementing the analysis of material efficiency. During the development of the analysis, the JRC-IES had regular discussions with the Lot 9 team to ensure consistency between both studies, and participated in the stakeholder consultations. Enterprise servers are also a relevant product group due to their content of hazardous substances, which are regulated by RoHS and REACH directives, but especially for their content of critical raw materials, and scarce and precious metals. Their high content of electronic components also makes them an interesting product group to be studied from a reuse and recycling perspective. The present study analyses potential material-efficiency benefits resulting from the reuse and recycling of certain components of servers. Several technologies that are already available for recycling servers and that guarantee the maximum recovery of certain materials are also discussed in this report. The report concludes by proposing potential material-efficiency criteria in the context of the Ecodesign Directive.

2. Goals and scope of the study

The objective of the present report is to propose and discuss potential requirements that could help improve the material efficiency of enterprise servers. The benefits of the potential resource-efficiency measures of those products are studied based on a quantitative analysis based on the Resource-Efficiency Assessment of Products (REAPro) method (Ardente and Mathieux 2012). The REAPro method assesses products by estimating their reusability/recyclability/recoverability indices, recycled content, use of priority resources, use of hazardous substances and durability, based on which it analyses the environmental and economic benefits of different End-of-Life (EoL) scenarios. The initial step is to carry out a literature survey about the product under analysis in order to harvest potentially useful data and information about its material efficiency. Data about the different lifecycle stages of the case study are then gathered, especially regarding the bill of materials (BoM), and the manufacturing, use and EoL phases. Once this information is obtained, an LCA is performed, and the REAPro indices are calculated to estimate the potential benefits of reusing and recycling servers under certain conditions.

3. Enterprise servers: analysis of literature and recovery practices

The number of published environmental studies on enterprise servers is still limited. The main aspect that limits more studies of this product group and other electric and electronic equipment is their complexity, and the lack of quantitative data about certain elements. In this section, we focus on two of the most relevant aspects to be defined before performing an environmental assessment of enterprise servers: the bill of materials (BoM) and end of life (EoL). We then summarise the results of several environmental assessments of enterprise servers. The results obtained help identify aspects to be further analysed in order to enhance the resource efficiency of enterprise servers.

3.1. Survey of the bill of materials

Gathering raw data on the bill of materials (BoM) for electronic products such as enterprise servers can be the most time-consuming task in carrying out an environmental analysis. On the other hand, the reliability of data may affect the quality of the results. In order to ensure data reliability, data sources that can be verified by the manufacturers of enterprise servers can be used. However, manufacturers are not always willing to disclose information on the material composition of their servers, and even when they are willing to give such information, that provided by the manufacturers involved in the initial steps of the supply chain can be very limited, so it is therefore difficult to obtain verified information from manufacturers. As result, we decided to undertake a detailed literature survey of the BoMs, including a short discussion about how data can be provided in different forms. Most of the information presented in this section was gathered from scientific papers published in peer-reviewed journals and technical reports.

First, we describe the components embodied in servers, and then we make a brief comparison of the quantitative data available.

3.1.1. Description of the components included in servers

As not all the studies in the literature are made of the same components, the results of the study-dependent BoM literature survey cannot be compared directly. Table 1 lists the components addressed by different case studies.

Table 1. Components and items included in enterprise server BoMs.

(Hannemann, Carey et al. 2010)	(Fujitsu 2010)	(Stutz 2011)	(Weber 2012)	(Teehan and Kandlikar 2013)	(BIO Intelligence Service 2013)
Main board	- Memory - Processor (CPU) including heat sink - main board component and printed circuit boards	-RAM memory -processors	-integrated circuits -printed circuit boards	- integrated circuits - printed circuit boards	Main board containing: - Processor - Memory - printed circuit boards - storage devices (HDD or SSD) - Controller/slots - Network and management
power supply	power supply	power supply	power supplies	power supply	power supply
hard disk drive	hard disk drive	hard drives	hard drives		
CD ROM drive	optical drive	DVD drive	optical drives		
chassis, outer panels, mounting rails	chassis		Steel, aluminium	casing	Chassis
cables	cable				
fans		fans			Active/passive cooling elements
floppy disk drive	keyboard		small electronic components		
screws	mouse				
interface cards					
internal mounting brackets					
external switches and LEDs					

CPU: Central processing unit; CD-ROM: Compact disk read-only memory; DVD: Digital video disk; HDD: Hard disk drive; LED: Light-emitting diode; RAM: Random-access memory; SSD: solid state memory drive

In some studies, processors, random-access memory (RAM) devices, integrated circuits (ICs) and printed circuit boards (PCBs) are included as part of the main board (also referred to as the motherboard) without explaining in further detail the differences between them. Other studies give a breakdown of components in the main board. The nomenclature and terms used in the technical specifications of servers is frequently different from that used in environmental analyses. The use of different terms to refer to the same component may lead to misunderstandings, especially among those that are not specialists in information and communication technology (ICT). A minimum description of the technical specifications of electrical and electronic components should therefore be given in BoMs.

Another observation is that, in many studies, auxiliary items such as screws, mounting brackets, and switches that do not directly affect the performance of enterprise servers are not included in the BoM, and are therefore not included in the environmental assessment.

In general, the components included in the BoM of most enterprise servers are:

- Main board, containing: ICs, including processor and RAM memory, and other PCBs
- Hard disk drive/s (HDD)
- Optical disk drive
- Fans (and other items regarded as heat sinks)
- Chassis/casing
- Power supply

3.1.2. Review of quantitative data

Quantitative data about enterprise servers can be displayed as: a) per component and expressed in terms of the number of components or mass, for instance 4 HDDs or 0.8 kg of HDD; b) per material composition, for example 11.7 kg of steel, 4.072 kg of aluminium, etc., without further explanation about which item or component contains which amount. Table 2 demonstrates how quantitative data is provided in the literature.

Table 2. Quantitative descriptions of enterprise servers.

	(Hannemann, Carey et al. 2010)	(Stutz 2011)	(Teehan and Kandlikar 2013)
Description of server	2U rack server	n.a.	rack server
Processor		2 units	
Main board (excl. processor)	1.40 kg	6 x 2 GB RAM	
Integrated circuits (ICs)			88[1] kg
Printed circuit boards (PCBs)			2.199 kg
Hard disk drives (HDDs)	0.80 kg	4 units	
Optical disk drive (ODD)	0.85 kg	1 unit	
Fans	0.6555 kg	4 units	
Chassis	6.9615 kg		8.767 kg
Power supply	4.15 kg	2 units	2.911 kg

n.a. not available. [1] Data regarding the ICs are given in: mass (g) and area (mm^2).

In addition to the mass of each component in the product, in some cases data is also provided per type of material. For instance, Hannemann et al. explain that a server is composed of 11.74 kg of steel, 4.072 kg of aluminium, 1.17 kg of plastic, 1.55 kg of copper, 0.7412 kg of iron and 1.412 kg of other materials (Hannemann, Carey et al. 2010). Ideally, such data should match that provided per component (illustrated in table 2), however as components are generally composed of a mix of materials, matching the information provided in these two formats is generally not possible. In some cases, it is due to the lack of information about the compositional data of components obtained from manufacturers at the beginning of the supply chain.

Where quantitative data is given in terms of units, additional research is needed to determine the mass of the components and the materials included in the product. Of all the components of enterprise servers, some merit further detailed study, namely PCBs and HDDs.

PCBs are part of a great number of electronic devices on the market. They are used as the support for interconnecting electronic components, which together provide diverse functions to the electronic product in which they are included. Therefore, PCBs are highly customised in order to provide certain functions, and their composition varies significantly depending on their type and number of functions (Hageluken 2006; Chancerel, Meskers et al. 2009).
Most information about PCB composition provided by industry comes from RoHS and REACH declarations. Both declarations only state the presence or absence of certain (usually hazardous) substances in the component, as opposed to full material declarations (FMD) which include all the substances present in the component, with their respective weights (Van Meensel, Willems et al. 2014). Although there are standardised formats for communicating FMD information by industry, such as the IPC-1752A, these are rarely available for PCBs and are limited to components or packages built into the boards (Association Connecting Electronics Industries 2012).

In general, most of the mass of PCBs is made up of semiconductor components (33%), capacitors (24%), unpopulated circuit boards (23%), electrical resistances (12%), switches and other materials (8%) (Tohka and Lehto 2005). From a material composition perspective, Takanori et al. estimate that PCBs are made up of approximately 30% of metallic materials such as copper and iron, 32% of organic resin materials containing carbon and oxygen, and 38% of glass materials used as resin-reinforcing fibres (Takanori, Ryuichi et al. 2009). Among the metals, copper used in circuitry has the highest content, followed by tin, iron and lead, which is mainly used in soldering and lead frames. Gold, silver and palladium are found in ICs as contact materials or plating layers. Although the material composition can be defined in general terms, there is no unique BoM for PCBs as their composition depends on the functionalities they should supply to the final product, as illustrated in table 3. PCBs can usually be classified as being of low, medium and high value depending on their content of precious metals, such as gold, as shown in table 4 (Hagelüken 2006).

Table 3. Breakdown of materials contained in printed circuit boards (PCBs) in various electric and electronic equipment (Hageluken 2006).

	Units	TV	PC	Mobile phone	Portable audio	DVD player	Calculator
Aluminium	%	10	5	1	1	2	5
Copper	%	10	20	13	21	5	3
Glass	%	6	18	2	-	-	13
Gold	ppm	20	250	350	10	15	50
Iron	%	28	7	5	23	62	4
Lead	%	1.0	1.5	0.3	0.14	0.3	0.1
Nickel	%	0.3	1	0.1	0.03	0.05	0.5
Palladium	ppm	10	110	210	4	4	5
Plastics	%	28	23	56	47	24	61
Silver	ppm	280	1000	1380	150	115	260
Tin	%	1.4	2.9	0.5	0.1	0.2	0.2
Others	%	15	22	21	8	6	14

Table 4. Classification of PCBs as low, medium and high value based on their content of gold (Hagelüken 2006).

Value	Gold concentration	Type of WEEE
Low	< 100 ppm	TV boards, monitor boards, (cordless) telephones, calculators, shredded bulk material after Al-/Fe-separation, etc.
Medium	100-400 ppm	PC boards, laptop and handheld computers, some mobile telephones, etc.
High	> 400 ppm	Circuit boards from mainframes, some mobile telephones, integrated circuits (ICs), MLCC capacitors

Although the main substances contained in PCBs are generally the same and do not change significantly from product to product, the material composition of PCBs is frequently given only for a limited list of materials that are relevant from an economic, environmental and even human toxicity point of view. Table 5 shows several examples of the metal content of PCBs. Although some of these papers were published more than 10 years ago, they are still cited by more recent publications (Jinglei, Williams et al. 2009; Park and Fray 2009). Most of the information included in table 5 is obtained from chemical analyses of PCBs. Unfortunately, in most cases the samples of PCBs analysed are mixtures of PCBs collected from different products. As a result, estimating the content of materials in the specific PCBs of one product using such information can lead to under/overestimations. In servers for which PCBs represent about 20% of the mass of the product, it becomes relevant to distinguish between low- and high-value PCBs in order to identify which PCBs can provide the greatest savings in terms of environmental impact and the greatest economic benefits from a recycling perspective.

Table 5. Average mass composition of PCBs (all in % weight, except values noted by * which are given as g/t).

	(Goosey and Kellner 2002)	(Veit, Pereira et al. 2002)	(Yuan, Zhang et al. 2007)	(Guo, Guo et al. 2009)	(Youssef, Ameer et al. 2012)
Aluminium	5.0	-	5.8	4.7	-
Copper	16.0	12.5	9.7	26.8	18.448
Iron	5.0	0.6	9.2	5.3	-
Gold	0.025	-	0.023	80*	0.039
Lead	2.0	2.7	2.24	-	-
Nickel	1.0	0.7	0.69	0.47	-
Palladium	0.01	-	0.01	-	0.009
Silver	0.100	-	0.06	3 300*	0.156
Tin	3.0	4.0	2.15	1.0	-
Zinc	1.0	0.08	1.16	-	-

3.2. Description of the end-of-life of enterprise servers

End-of-life (EoL) scenarios are generally described briefly in the environmental assessment for servers, as most studies concentrate on defining the lifecycle phases that have greater impacts, mainly the extraction and manufacturing of materials, and use of the product. Quantitative information available in the literature about the EoL of enterprise servers is also frequently omitted (Teehan and Kandlikar 2013). While Weber included the EoL for the assessment of the carbon footprint of a server, the paper only discloses in detail the method used (PAS2050) for the allocation of metals without explaining in further detail the processes included at the EoL stage (British Standard Institute 2011; Weber 2012). Other publications focused on the EoL of a specific component found in servers, such as HDDs or PCBs (Yan, Xue et al. 2013). Table 6 summarises the information about aspects related to the EoL of servers in various papers.

Table 6. End-of-life (EoL) aspects of enterprise servers discussed in the literature.

Aspects related to EoL	(Fujitsu, 2010)	(Weber 2012)	(Stutz, 2011)
Lifetime	The server is recycled after the anticipated lifetime of 5 years	The most likely lifetime is 6 years, whereas the minimum/maximum values are 3 and 10 years	Not mentioned
Reuse	Components are reused or resold	Not analysed	Not analysed
Recycling	Disassembly/dismantling almost exclusively by hand. Recycling of keyboard, mouse, packaging and manuals is considered. Recycling rate including thermal recovery > 90%		Server sent to recycler at the end of the first customer use. It was assumed that 75% of the server is recycled while the rest is incinerated for energy recovery

At present, some parts and components of enterprise servers are regularly extracted to be reused in other servers and, more recently, recycled using a specific treatment process. Fujitsu explains that enterprise servers are disassembled/dismantled[9] to extract memory devices (HDDs, memory cards and expansion cards), cables, batteries and mainboards from the chassis, as described in Fujitsu (2010). These components are either reused in new or remanufactured servers, or recycled using a combination of mechanical, chemical and thermal processes. The remaining components in the server are shredded, and the remaining fraction is incinerated.

Overall, information about the EoL of servers in the literature is rather scarce and does not disclose detailed quantitative data about the current processes used to treat servers, nor the potential benefits of their reuse and recycling. A part of the current report aims to illustrate more precisely how enterprise servers are managed at their EoL, including reuse by original equipment manufacturers and specialised workshops, and recycling. This includes some ongoing developments concerning the automatic disassembly of electrical and electronic equipment, especially of PCBs as, given that they have the highest concentrations of valuable materials, their selective recycling is key to the economic sustainability of the collection and recycling of electronics.

[9] The terms ‘dismantling’ and ‘disassembly’ of a product (or its parts) are generally used in the literature as synonyms when referring to recycling processes. However, there is a slight difference between the two terms: the former mainly refers to the careful removal/extraction of the part (e.g. for substitution, reuse or repair), while the latter refers to the removal/extraction of the part in a way that could potentially destroy the functional integrity of the product [Ardente, Mathieux et al., 2014].

3.2.1. Reuse of enterprise servers

3.2.1.1. Reuse by the original equipment manufacturers

Enterprise servers are mainly a business-to-business (B2B) product, which means that a large number of these devices are managed by original equipment manufacturers (OEMs) even during their EoL, and rarely reach recycling facilities. Instead, this product generally reaches recycling facilities after possible reusable parts have been harvested and tested for their possible reuse for second-hand equipment. The OEMs of servers are aware of the economic value of their products even when they are technologically obsolete or no longer function. Therefore, most OEMs have developed their own EoL policies to optimise the reuse and recycling of components, and to prevent the re-manufacturing of new parts, thus helping to save natural resources and reduce waste generation.

Figure 1 shows an example of the various stages of a used enterprise server. For the OEM, the first stage is to verify the parts included in a server that is due to be dismantled/disassembled. The inventory list of these parts is updated regularly to get more comprehensive understanding of the potential stock likely to be returned. OEMs check the correspondence between failed parts claimed by customers and parts received at their facility. Such cross-checking can be made in some cases thanks to barcodes included in the form of labels that contain information about the manufacturing year, place, serial number of the equipment, where it was used and the number of times it was repaired, among other information. Once the parts are verified, they are either classified as stock or due to be recycled. Parts classified as stock are first tested to check that they work correctly and can be used in the future. Repair costs are requested for failed parts. Parts are repaired or discarded depending on the costs and stock availability. Some OEMs will only repair the same part once, whereas others may have a more flexible internal policy for their products. In some cases, parts suspected of being faulty are tested and, depending on the outcome of the test, they are sold to brokers (companies specialised in the purchase of used electronic parts) or classified as scrap for recycling. Some functioning parts can be stocked for future reuse. Some customers often request that memory cards and software be upgraded. Expansion and graphic cards are among the most frequently replaced parts. Power supply units are not normally replaced unless there is a significant upgrading of the server, and more power is needed.

Some OEMs offer their clients the possibility to acquire a ‘refurbished server’. These are built from “used” and “repaired” parts, and are generally traded as “reconditioned/renovated” goods. These servers are less costly but are fully functional (from a technological standpoint) and tested using newly built machine protocols. They can also be upgraded with more recent technology, if requested by the customers. Refurbished servers are often configured according to client requests. Once the client configuration is defined, the OEM looks for the closest existing configuration in its stock.

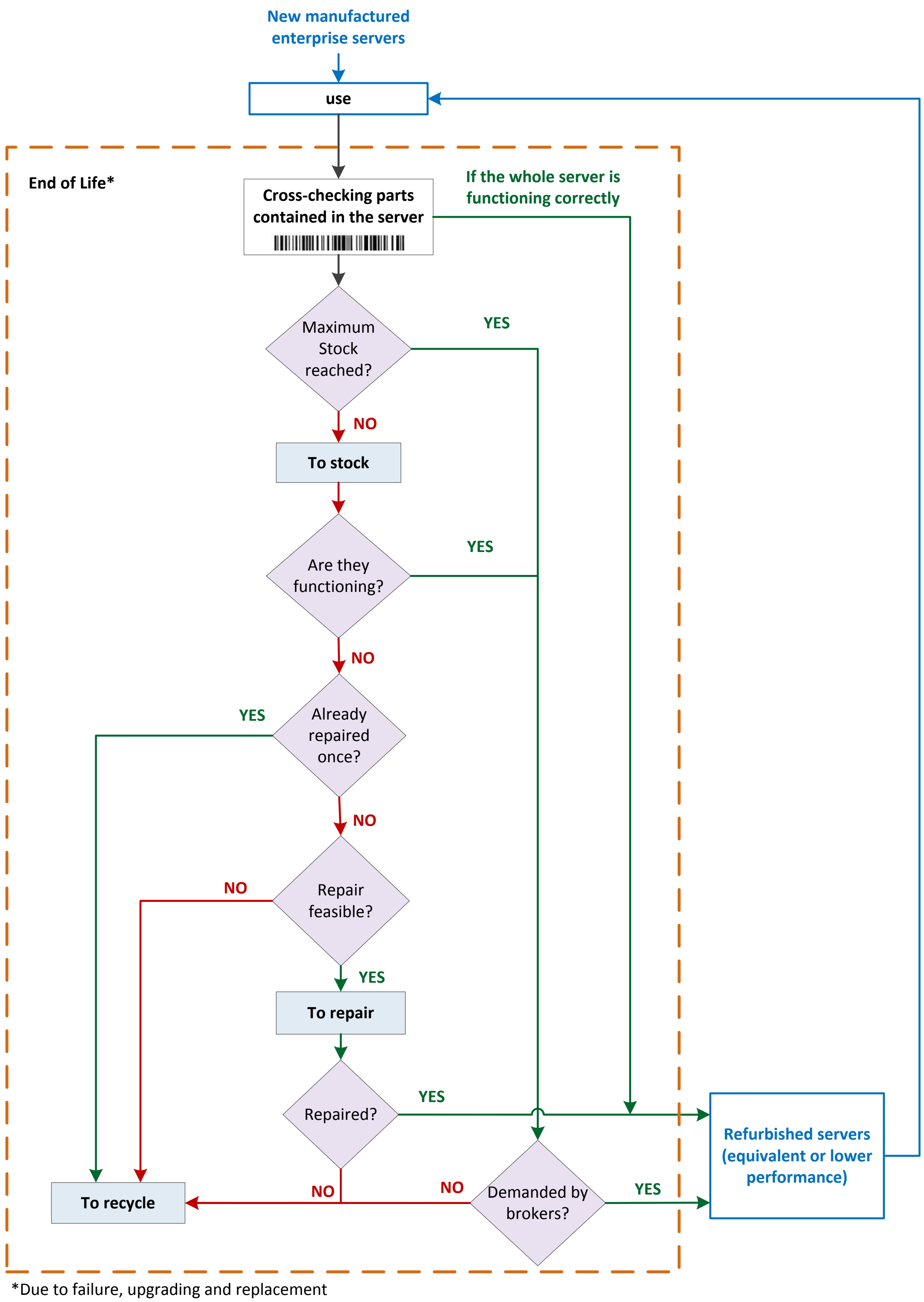

Figure 1. End-of-life (EoL) management of servers by their original manufacturer.

3.2.1.2. Reuse by specialised workshops

It is difficult to find statistical information about parts that are frequently replaced and reused in servers. Original equipment manufacturers tend to keep this information confidential. The only way to gather such data is by consulting IT refurbishing companies. In this section, we provide statistical data from a refurbishing company operating in the United Kingdom called Re-Tek. The information and data provided help shed light on several aspects of the reuse of servers and their parts. First, a short description is given about the end-of-life of various servers collected by this company. Second, we provide information about the parts most frequently harvested from servers for reuse.

Servers that reach the refurbishing workshop are generally sold as full units, recycled or harvested for spare parts. The flow of incoming servers is more or less equally distributed to each of these processes. Generation 2 and 3 servers are generally sent for recycling, whereas generation 4 are used to harvest certain parts, and the more advanced versions (generations 5 to 7) are resold or kept in stock as there is a demand for them on the second-hand servers market. Most of the servers reaching the Re-Tek refurbishing facility are rack-mounted models manufactured by Dell and Hewlett-Packard (re-tek 2015). According to the data received, the most popular model resold is the generation 5 Hewlett-Packard ProLiant DL360 server. Table 7 lists some of the models generally reused.

Table 7. Enterprise server models reused in workshops during 2014.

Manufacturer	Models	Manufacturer	Models
Dell PowerEdge	1850	Hewlett-Packard ProLiant	Intel 3 series (360,380) - Generations G5 to G7
	2850		AMD 3 series (365,385) - Generations G5 to G7
	6000 series		500 series - Generations G4 to G7
	T/R series		100 series (120,160) - Generations G5 to G7
			C Class blades Generations G5 to G7 - G4 used for spare parts

Most of the parts contained in the server are harvested: main boards, raid SMA cards, network cards, power supplies, chassis, processors and memory cards greater than 1 024 MB capacity. Memory cards with a capacity lower than 1 024 MB, and HDDs with certain capacity (36-146 GB) are not normally harvested. Figure 2 shows the spare parts most frequently reused in servers. The most popular HDDs replaced are those of 300 GB capacity. The most frequently reused memory cards are those of 2 048 MB capacity. The Xeon dual, Xeon Quad and Dual Quad Xeon processors are the most frequently reused processors.

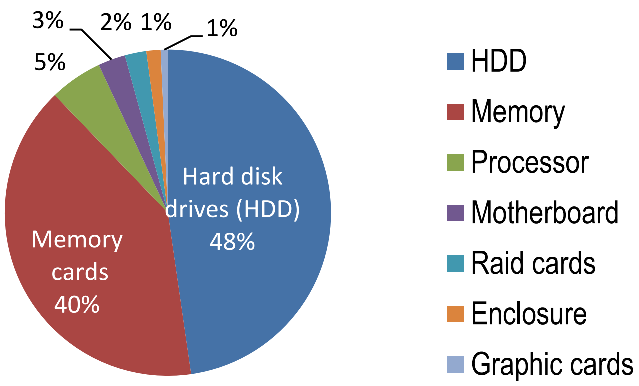

Figure 2. Spare parts most frequently replaced in servers (Re-Tek, 2015).

In 2014, the non-profit foundation Free ICT Europe (FIE) was created to actively promote the secondary information and communication technology (ICT) market within Europe. FIE is composed of independent small and medium enterprises (SMEs), and is characterised by a highly skilled workforce. It represents over 50 000 European jobs in a market worth 30 billion Euros. The emerging secondary software market is expected to be worth 90 billion Euros, and generate an additional 100 000 jobs by 2017 (Van Oostrum, Auchere et al. 2015).

Actors involved in the reuse of servers are regarded as independent operators, and include brokers, spare parts repairers, spare parts providers and third-party maintenance (TPM) providers. Brokers are most focused on reselling refurbished servers, whereas spare parts repairers and providers concentrate on harvesting spare parts from used servers. Brokers generally buy complete used server units with the aim of upgrading and/or refurbishing them for later resale on the market. In some cases, brokers may also harvest and sell spare parts, although this is not their core business. Spare parts repairers and providers (SPRP) are mainly maintenance oriented, so they are interested in accessing spare parts. SPRP generally test whether servers and their parts run according to the specific conditions defined by the manufacturer (OEM), if so, spare parts are harvested and stocked to be sold on to TPM companies. TPM companies are generally contracted to maintain the ICT equipment of companies that are not specialised in ICT. TPM companies are especially active in data centres. They provide on-site support normally to quickly fix and repair ICT equipment, and therefore are well-linked with SPRP. Figure 3 illustrates the reuse of servers by independent operators (in dark green). Services provided by independent operators include maintenance, firmware updates, upgrades and sale of servers (all highlighted in purple).

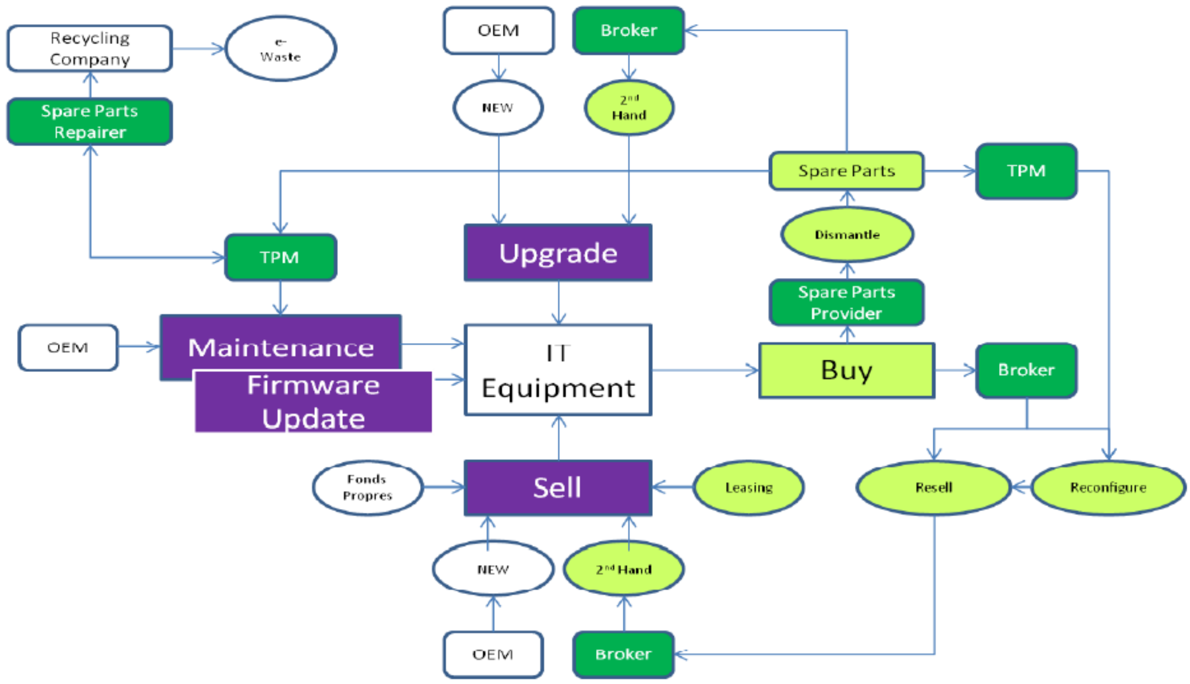

Figure 3. Roles of independent operators in the ICT equipment sector (Van Oostrum, Auchere et al. 2015).

3.2.1.3. Limitations on the reuse of servers

From an organisational point of view, several different actors are involved in facilitating the reuse of complete servers or their parts, which has led to the creation of a secondary market for the product. Leasing companies, independent maintenance providers, and spare parts repairers and providers play key roles in the establishment of this competitive secondary ICT market (Van Oostrum, Auchere et al. 2015). Leasing companies provide organisations with financial alternatives with regard to the cost of acquiring new equipment. Independent maintenance providers, and spare parts repairers and providers supply maintenance services at reduced costs compared to the OEMs. In this study, we limit our analysis to potential restrictions on the reuse of components included in enterprise servers from a product perspective. Such restrictions relate mainly to the availability of firmware and data deletion. How these aspects can restrict reuse is explained in further detail in the following sections.

3.2.1.3.1. Availability of firmware

The decision to reuse ICT equipment and their parts depends on the availability of firmware updates (Van Oostrum, Auchere et al. 2015). Firmware is a set of micro-instructions which activates hardware functions designed by OEMs. In other words, firmware is a type of software that makes the server work, and can be understood as the 'cables' that bring together all the parts contained in the server so that they function correctly. Firmware contains bugs and fixes. Bugs are used by customers to update the firmware and make the IT equipment more reliable. Fixes are new micro-instructions designed by OEMs to replace defective ones. Some parts of the server require specific firmware in order to function, and in some cases obtaining the licenses to such firmware can be an obstacle to the reuse of parts.

The most basic enterpriser server includes a processor, memory devices, input/output interfaces and power supplies. All these parts are interconnect and assembled together to form the server, and must be compatible in order to work well together. The most important way to ensure such compatibility is to proceed with firmware updates. A single modification in a software or update generally leads to multiple changes in other interconnected components, and even in the whole customer chain. Therefore, the availability of firmware is crucial to allow the reuse of functioning parts in servers.

The availability of firmware affects the use and reuse of IT. As servers normally work in connection with other enterprise servers to create clusters of enterprise servers, and data is stored in disks and storage area networks. Firmware updates are crucial for maintenance operations involving the replacement of spare parts or modifying the network. For instance, a firmware update can remedy data access errors, but such an update will also generate the need to update other related components of the cluster and network, which requires access to further firmware updates.

3.2.1.3.2. Data deletion

Storage devices such as HDDs and memory cards cannot be reused without ensuring data deletion, referred to as “data sanitisation”. In general, sanitisation is defined as the process of eliminating sensitive information from a document or other medium (i.e. digital media such as HDDs and SSDs). Sanitisation attempts to reduce the document's classification level, possibly rendering it an unclassified document. Table 8 summarises some existing standards about data sanitation and deletion of hardware (See also Table A1 in the annex).

Table 8. Standard for data deletion published per country. Based on (Hintermann and Fassnacht 2008; Fisher 2015).

Country	Standard	Overwriting (number)	Description of overwriting cycles
USA	DoD 5220.22-M (US Department of Defence)	3	first: zero second: one value third: random character
	NCSC-TG-025 (US National Security Agency)		
	AFSSI-5020 (US Air Force)		
	AR 380-19 (US Army)	3	first: random character second: specified character (i.e. zero) third: complement of the specified character (i.e. one)
	NAVSO P-5239-26 (US Navy)	3	first: specified character (i.e. one) second: complement of the specified character (i.e. zero) third: random character

Country	Standard	Overwriting (number)	Description of overwriting cycles
Canada	RCMP TSSIT OPS-II by the Royal Canadian Mounted Police	7	first: zero second: one third: zero fourth: one fifth: zero sixth: one seventh: random character
	CSEC ITSG-06	3	first: one or zero second: complement of the previously written character (i.e. one if "first" was zero) third: random character
Germany	VSITR-Standard (Federal Office for Information Security)	7	first: random bit pattern second to sixth: reversed bit pattern (i.e. zero is replaced by one and one is replaced by zero) seventh: overwriting by fixed '01010101' pattern
United kingdom	HMG IS5 Communications-Electronics Security Group (CESG) (UK Government Communications)	3	first: zero second: one third: random character
New Zealand	NZSIT 402 (Government Communications Security Bureau)[10]	1	first: random character
Russia	GOST R 50739-95	3	first: zero second: random character third: random character
Australia	ISM 6.2.92 (Australian Department of Defense)[11]	1	first: random character

The 5220.22-M standard for clearing and sanitization developed by the US Department of Defence includes processes for different types of media (see Table A2 in the annex). The standard makes a distinction between clearing and sanitisation. Clearing is defined as "a method of sanitisation by applying logical techniques to sanitize data in all user-addressable storage locations for protection against simple non-invasive data recovery techniques using the same interface available to the user; typically applied through the standard read and write commands to the storage device, such as by rewriting with a new value or using a menu option to reset the device to the factory state (where rewriting is not supported)". Sanitisation is defined as "a process to render access to target data on the media infeasible for a given level of effort (i.e. clear, purge, damage, and destruct)". In other words, clearing refers to non-destructive methods that allow the device to be reused once data has been deleted, whereas sanitisation relates to destructive treatments further to which the device cannot be reused. For example, Dynamic random-access memory (DRAM) can be both cleared and sanitised. It can be cleared by overwriting all addressable locations with a single character or by removing all power, including battery power. Sanitisation can be done by destructive actions, such as disintegration, incineration, pulverisation, shredding or melting. Devices that have been sanitised cannot be reused. Data is generally sanitised by physically destroying

[10] More information: http://www.gcsb.govt.nz/assets/GCSB-Documents/NZISM-2011-Version-1.01.pdf
[11] More information: http://www.asd.gov.au/publications/Information_Security_Manual_2014_Controls.pdf

storage media through shredding, degaussing and thermal processes. By shredding, memory devices are shredded into smaller pieces/particles. By degaussing, disks (also referred to as plates) are exposed to a strong magnetic field. Data on these plates, including the service and maintenance information, is deleted permanently, which makes the device impossible to be reused afterwards. By thermal destruction, data in disks are destroyed after exposing the surface of the disks to temperatures above the Curie temperature of the coating used (766 ºC).

In conclusion, standards to ensure data deletion are crucial to facilitating the reuse of data storage devices contained in enterprise servers. The absence of a guarantee that data contained will be completely deleted can significantly affect the number of these components likely to be reused. As there are many different methods available to ensure data deletion, data storage devices can be reused to help extend their lifespan and generate material savings for some electronic products.

3.2.2. Recycling of enterprise servers

As discussed at the beginning of this section, current literature estimates that the recycling rate for servers varies from 75% to 90% (when thermal recovery is included), but does not describe the processes included in recycling (Fujitsu 2010; Stutz 2011). While Fujitsu (2010) mentions that disassembly/dismantling is carried out almost exclusively by hand, with the aim of separating some parts that will be treated selectively, no description of those later treatment processes is given. PCBs are among the most relevant components in servers, and are also being used more frequently in other electrical and electronic equipment. They represent about 20% of the mass of servers. The greatest amounts of valuable metals in the server, such as copper, gold, palladium, and silver, are almost exclusively concentrated in the PCBs. Such content varies depending on the functionalities of the PCB, and also depending on the type and number of electronic components included. Several of the PCBs in servers have high concentrations of valuable metals, especially the main boards and memory cards. In order to improve the recycling rates of copper, gold, palladium and silver, these PCBs need to be separated from the server to undergo selective recycling treatments.

In 2014, WRAP published a report illustrating how PCBs are recycled in the United Kingdom (UK) (McCoach H, White C et al. 2014). The research analysed four key techniques currently used: fully manual segregation, fully manual segregation with reuse of some components, semi-automated separation with commercial shredding, and semi-automated separation with commercial smashing. Fully manual segregation refers to the harvesting of target components from other Waste of Electrical and Electronic Equipment (WEEE) streams, followed by the manual dismantling of equipment. Semi-automated separation with commercial shredding involves the mechanical shredding of WEEE for size reduction and separation of saleable ferrous and non-ferrous metals, and manual picking operations downstream to recover PCBs and other components. This technique is used to recover PCBs from items that cannot be cost effectively segregated manually or components to which PCBs are physically attached (e.g. welded). By semi-automated separation with commercial smashing, components that require manual recovery are manually separated from other streams, and the remaining WEEE is treated by spinning and smashing to obtain smaller components that will undergo magnetic separation, and finally manual picking lines. The study concludes that the fully manual segregation with reuse captures most value from PCBs, as losses of valuable materials are significantly minimised. PCBs recovered using this technique can achieve a value several times greater than the cost of their recovery.

Research has been developed to further advance automatic disassembly in order to selectively treat PCBs in such a way as to recover the maximum possible amount of valuable metals. Even though the automatic disassembly of products has long been discussed, no fully operational commercial facilities currently offer this service. We gathered information from ongoing research to provide a brief overview of the state-of-the-art of automatic disassembly technologies which are currently being tested and may become feasible for use in the future. The following section describes how these pilot facilities are being developed, and aims to forecast the near-future evolution of disassembly, and the harvesting of relevant components and electronic packages rich in certain metals. The application of the different technologies described below for recycling enterprise servers would increase the amount of valuable metals recovered from PCBs.

3.2.2.1. Developments for the automatic disassembly of products containing printed circuit boards

As part of the present study, we visited a pilot plant being developed at the Institute of Industrial Technologies and Automation of the National Research Council of Italy (ITIA-CNR) in Milan. This pilot plant aims to use a new systemic approach for the sustainable recovery of both key metals and the non-metallic fractions of PCBs. The research activities are carried out in close cooperation with the Department of Mechanical Engineering at the Politecnico di Milano.

The pilot plant is composed of three sections, referred to as cells hereafter. Macro components are separated in Cell 1 (i.e. PCB is extracted from equipment). This cell is designed to be managed first by one operator using a 'small scale' robot to assist in the use of different tools (the robots are shown in the picture to the left in Figure 4). Two other robots are programmed to mimic and automatically replicate the disassembly sequence followed by the operator. This section also has a conveyor belt which transports PCBs for storage and remanufacturing (conveyor belt is shown in the picture to the right in Figure 4).

Figure 4. Photographs of Cell 1 for the automatic disassembly and handling of PCBs at ITIA CNR.

Cell 2 includes two sub-sections: the testing of the functioning of PCBs, and the remanufacturing of PCBs where micro-components and electronic packages are automatically harvested and replaced in PCBs (see figure 5). Both sub-sections work based on patterns and information about the functions of the board and the electronic packages contained, all such information needs to be previously provided by the PCB manufacturers. Re-manufactured PCBs can re-enter the manufacturing lines to be included in newly manufactured products or refurbished products.

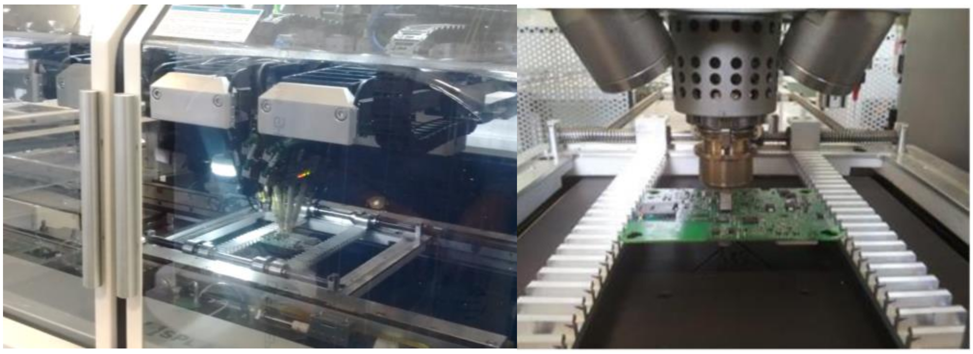

Figure 5. Pictures illustrating the two sections of Cell 2 for the testing (left), and automatic disassembly and replacement (right) of components in PCBs at ITIA-CNR (Colledani, Copani et al. 2014).

Cell 3 (shown in figure 6) aims to separate metal and non-metal fractions of the materials contained in PCBs. The first step is a gentle shredding (8-10 mm) of PCBs, then the whole fraction is sieved and separated into different fractions (2 mm, 1.2 mm, 0.6 mm). At that point, each of the fractions can undergo different treatment depending on the particle size and the target: Eddy current separator (> 2-3 mm), corona electrostatic separation (< 2-3 mm) and imaging inspection. Eddy current separators use a powerful magnetic field to separate non-ferrous metals from waste after all ferrous metals have been removed. Corona electrostatic separation (CES) separates particles based on their conductivity. Cell 3 includes automatic visual identification of electronic packages, thereby predicting the economic value of each PCB before the process. At present, electronic packages are identified by image analysis, and the amount of materials contained is estimated based on a knowledge-based system that considers 'material declarations', when available from packaging manufacturers, or predictions based on statistics. The difference in the estimations of the mass of valuable metals in electronic packages based on knowledge-based forecasting and chemical analysis is about 5% (Colledani, 2014).

Figure 6. Cell 3 for recycling PCBs and/or some of their components at ITIA-CNR.

This pilot plant has been designed to ensure maximum flexibility, so that for instance a PCB can be treated in Cells 1 and 3, without going through Cell 2, or can first be treated in Cell 2 to extract a specific package and then proceed to Cell 3. Moreover, inside each cell, the material flow can be re-directed depending on the specific properties of the product or mixture being treated. From a future recycling perspective, it may become interesting to separate certain micro-components or electronic packages (second part of Cell 2) to subsequently carry out the selective recovery of a material from specific types of components (i.e. tantalum contained in capacitors, gold fingers from memory cards).

3.2.2.2.Visual inspection technologies developed by the GreenElec project

The visual inspection of PCBs is also being developed in the framework of other research projects as a possible way to separate different types of e-waste and identify metals in PCBs. For instance, as part of the GreenElec project, Refind Technologies has developed the e-grader: a technology that has the unique ability to grade and sort used electronic products based on their current and optimal downstream values (Melin 2014). The e-grader uses deep learning technology, based on data scanned by a specifically designed test bench to determine the make and model of each product in real time. The system provides an efficient pre-sorting of large volumes of devices such as phones, tablets, etc. During the project, a total of 200 PCBs from flat-panel displays and 250 LED lamps were scanned. The e-grader was able to sort more than 75% of the individual objects using no auxiliary methods, and 95% on type level. For LED lamps this meant that the product was identified, but not the individual model or brand (Melin 2014). Figure 7 has two pictures of the e-grader. The picture on the right shows in more detail the conveyor belt on which objects are placed for classification.

Figure 7. Pictures illustrating the e-grader at Refind technologies (Refind 2015).

The GreenElect project has also developed a tool to identify the materials contained in PCBs (Philips Group Innovation Research 2012). The process includes four major steps:

1) Obtain the layout of a particular PCB design
2) Use computational geometry to calculate the actual volumes of various parts of the PCB (copper, solder mask, dielectric)
3) Gather data on the various substances present in the PCB
4) Translate volume fractions into weight fractions, combining the results from the second and third steps

Data about the substances present in PCBs is gathered from each component's BoM, the available full material declarations, or via other developed models. The total material composition of the PCB is established by adding up all the substances. Within the same package type, there may be variations on some of the package dimensions as the die size can vary from covering almost the entire surface of the component, to covering less than half. This also affects the length of the bond wires. Dimensions are estimated by assuming an average value.

Figure 8 shows a screenshot of a software tool developed within the GreenElec project, to show the distribution of a specific material on a PCB. The figure shows the distribution of gold on the top side of a PCB of one of the project's test case products. On the top right side, there is a drop-down list from which any substance present on the board can be selected. The components showed coloured contain all the selected substance. The colour code goes from blue to red to illustrate how much of that substance is present in absolute value.

Combining the technologies developed within GreenElec leads to more accurate values of the content of materials in PCBs and their potential recycled value. Figure 9 shows an example of the output information that both tools can provide. As illustrated, information can be given on the aggregated weight (in grams) per material (top-right image), and economic value of the different materials contained in a product (lower-left and lower-centre images).

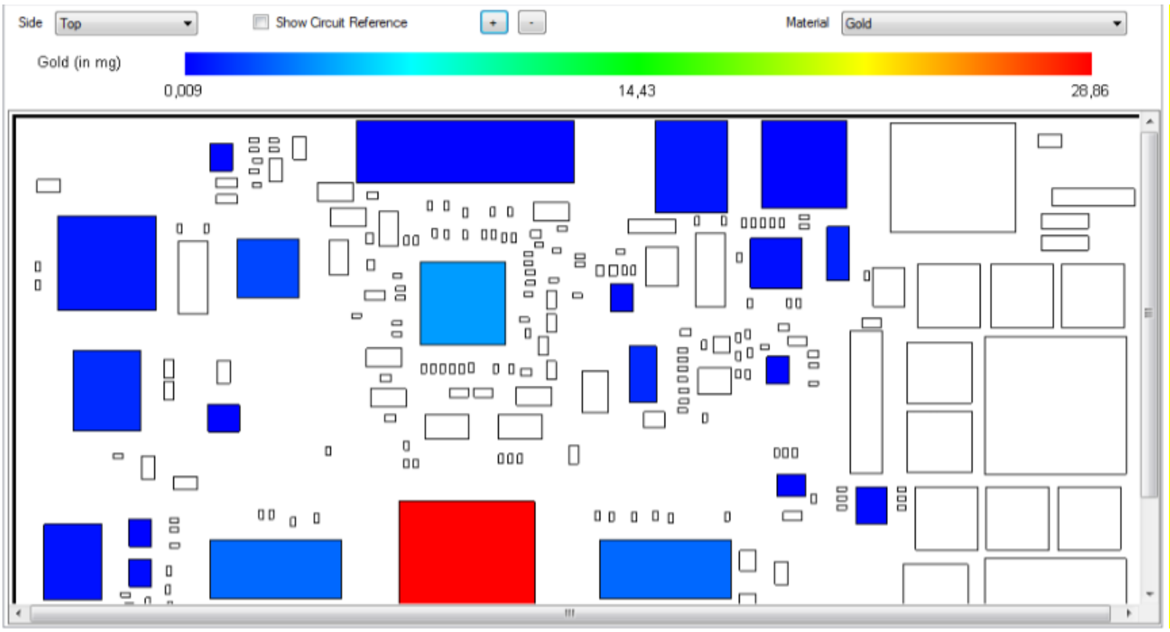

Figure 8. Gold distribution on printed board assembly components (Van Meensel, Willems et al. 2014).

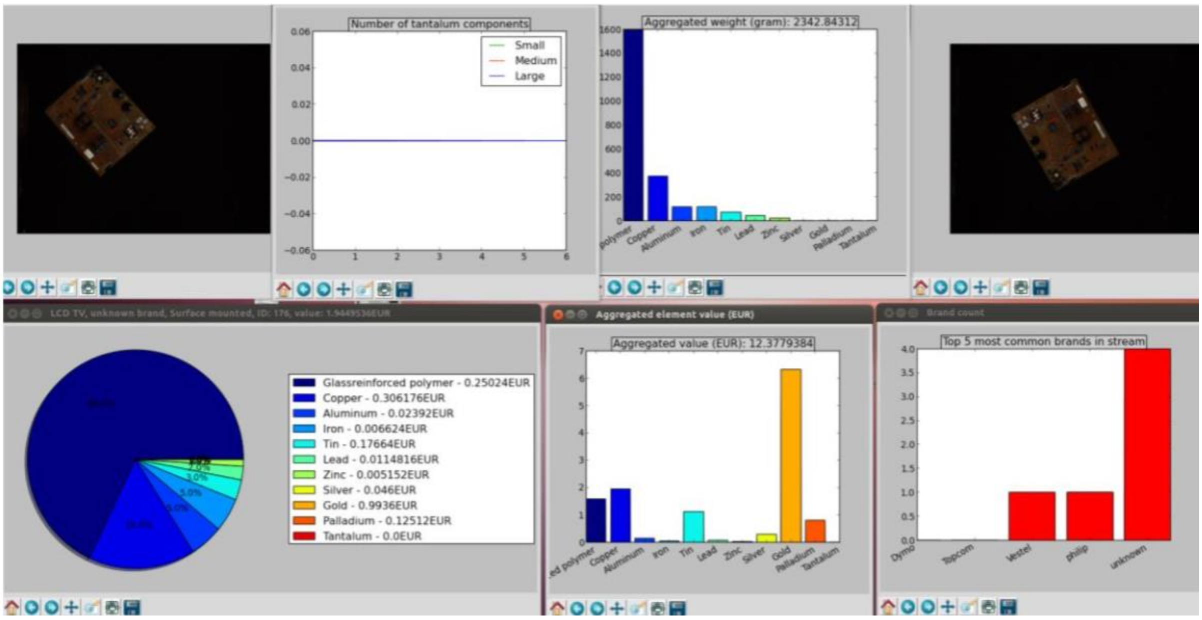

Figure 9. Detailed information on the composition of PCBs scanned using GreenElec tools (Melin 2014).

3.3. Survey on environmental assessments of enterprise servers

Two types of environmental assessments for enterprise servers are available. Those normally performed by information and communication technology (ICT) manufacturers to inform consumers about the environmental impact of their ICT equipment (Fujitsu 2010; Stutz 2011; Apple 2012), and a second type of studies that analyse enterprise servers as case studies to illustrate certain environmental methodologies (Marwah, Shah et al. 2011; Weber 2012). In most cases, the environmental impact is almost always estimated by the carbon footprint of the product and the quantitative results, if included, given as carbon dioxide equivalents (CO_2 eq.) This section summarises the outcomes of these studies.

IT manufacturing companies like Fujitsu, Dell and Apple have published different environmental reports on enterprise servers. Although the contents of some of these reports differ, all use the carbon footprint methodology to explain the environmental impact of their servers. In addition, each report concludes that the use phase generates about 90% of the total environmental impact, manufacturing contributes from 5 to 7% to the footprint and the remaining impact is due to transport and recycling (Fujitsu 2010; Stutz 2011; Apple 2012).

The environmental assessment of a PRIMERGY TX/RX300 S5 server from Fujitsu includes a sensitivity analysis which shows that the total carbon footprint (assuming a 5-year lifetime) can vary from 980 to 3 750 kg CO_2 eq., depending on the energy mix of the energy supply of the country (i.e. depending on the share of nuclear power, coal and lignite power generation). This assessment also estimated that the total carbon footprint can reach almost 5 000 kg of CO_2 eq. when the server works at its maximum capacity (Fujitsu 2010).

Stutz estimates that the total carbon footprint of a Dell PowerEdge R710 in the US is about 6 360 kg CO_2 eq. (assuming 4-year lifetime) (Stutz 2011). The manufacturing phase, which generates about 5 to 7% of the environmental impact, is dominated by the manufacture of four components: the main board (including processors), the hard drives, the chassis and the network cards, which account for up to 90% of the total emissions. In general, the carbon footprint of a server is 18 times that of a laptop and 8 times that of the desktop. This large difference is mainly due to the relatively high amount of power used and the fact that servers run continuously during their complete lifetime.

In 2012, Apple published an environmental report on a small-scale server (Mac mini OS X server) (Apple 2012). Customer use is also identified as the stage which generates the greatest amount of greenhouse gas emissions (over 75%), followed by production (20%). In their environmental report, Apple include other aspects such as for instance the fact that they use 68% less plastic than the first generation of the server by substituting the enclosure with recyclable aluminium, and also that the corrugate and paperboard packaging used contains at least 50% recycled content. The Mac mini server complies with the RoHS for electrical and electronic equipment, and it is characterised by a limited content (up to 900 ppm) of brominated flame retardants (BFR) and polyvinylchloride (PVC) in internal cables and AC power cords (Apple 2012).

Marwah, Shah et al. performed an environmental analysis to identify the "hotspot" of the PCBs of an enterprise server, i.e. the part that has the greatest environmental impact during the manufacturing stage (Marwah, Shah et al., 2011). The 'automated' lifecycle assessment (LCA) proposed allows the user to select inputs from the existing product inventory in order to obtain an approximate assessment of all components. Such automated LCA requires two databases: a product database containing the BoM, and another database including the environmental impact of various components (e.g. Ecoinvent). The use of the automated LCA allows the number of items under study to be reduced from about 560 components to 22 clusters, which simplifies the list of materials used in the environmental database. The 'hotspot' analysis helps identify which component contributes most to the environmental impact. In the PCB of an enterprise server, the application-specific integrated circuit (ASIC/logic) contributes almost 75% of the environmental footprint of the PCB. The second and third largest contributors (making up almost 20%) are connectors and capacitors.

Weber calculated the carbon footprint of an IBM rack-mounted electronic server manufactured in 2008, and compared it with the carbon footprint of a personal computer (Weber 2012). The study was carried out to better understand the quantitative uncertainties within a carbon footprint analysis. The total carbon footprint for an IBM server, assuming a lifetime of 6 years, is about 6 700 kg CO_2 eq. Among all the stages, the use phase has the greatest carbon footprint and uncertainty level (50%). This high level of uncertainty is due to the different assumptions regarding its useful lifetime, the variability in electricity mixes in different market regions, and the use profile, as already discussed by (Fujitsu 2010).

Figure 10 shows the carbon footprint of the production of diverse components (approximately 340 kg CO_2 eq.), and of the packaging and logistics stages (approximately 40 kg CO_2 eq.) for servers and a desktop computer. As illustrated, over 65% of the carbon footprint is due to the production of integrated circuits, the board of the PCBs, HDDs and ODDs, and other components, as anticipated by (Stutz 2011). The uncertainty of the production phase remains moderate (15%). However, data on the manufacturing phase is likely to have been greatly underestimated due to data limitations. The inventory data for the BoM of the server is based on Ecoinvent data for desktop computers, which was modified to match the analysis of enterprise servers. For instance, only two datasets were available for PCBs and both were relatively old. Although the carbon footprint of delivery is relatively low compared to production, the uncertainty remains considerable (25%). Such uncertainty is mainly due to the geographical variability of the various scenarios rather than parameter itself.

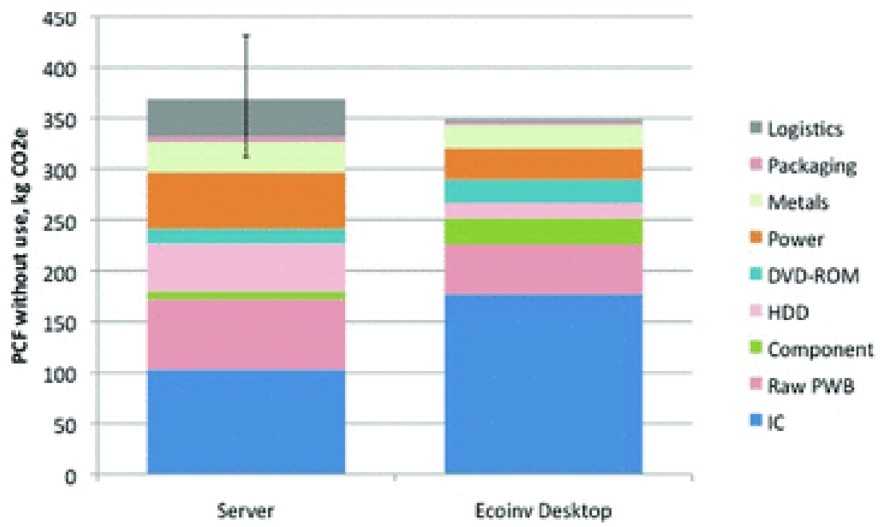

Figure 10. Average results for the product carbon footprint (PCF) of the production and recycling of servers by subgroup of components (PCF values displayed excludes use) (Weber 2012).

In 2013, Teehan and Kandlikar quantified the greenhouse gas emissions of the manufacturing of 11 ICT products, including large and small-scale desktop and laptop personal computers, a thin client device, an LCD monitor, several types of mobile devices such as tablets, a network switch and a rack server (Teehan and Kandlikar 2013). They estimated the emissions by using primary data from hand disassembly and the Ecoinvent v2.2 database. Emissions for a rack server are estimated at 360 kg CO_2 eq., not far from the 380 kg CO_2 eq. estimate made by Weber (Weber 2012). Their paper includes a detailed and complete description of the BoM of the rack server analysed, but does not quantify the environmental impact of the use phase and the EoL. In any case, the study provides a good description of how the environmental assessment of ICT equipment is carried out using LCA software.

Hannemann, Carey et al. estimated the resource consumption of an enterprise server using exergy analysis (Hannemann, Carey et al. 2010). The server analysed was a 2U rack-mounted unit containing two Intel Pentium III 1.0 GHz processors, one 36 GB SCSI HDD, one CD-ROM drive, one floppy disk drive and numerous peripheral ports and other components. The total exergy consumption included that used for the material extraction and processing, manufacturing, transportation, operational power and cooling, and recycling. The server was analysed operating at 50% peak power consumption for two types of cooling settings: 100% internal fan cooling and 100% external cooling load (which is the general scenario addressed by most enterprise server data centres). The total exergy consumption when using external cooling is 2.5 times that of using internal cooling (15.68 GJ). In both cases, the exergy consumption of the power supply and cooling represent 82% and 93% respectively of the total consumption, whereas the material extraction represents about 15% and 6% respectively. The results of this study show that the use phase is the stage that consumes the greatest amount of resources, thus generating the greatest environmental impact. The stage of the extraction of materials has a lower impact than the use of other ICT devices such as desktop and computers, mainly due to the fact that they operate continuously, 24 hours a day, for 4 to 6 years.

In conclusion, most of the studies carried out on enterprise servers focused on the carbon footprint to explain their environmental impact. As information regarding other environmental impact aspects (i.e. acidification, eutrophication, abiotic and biotic depletion) is generally missing, environmental analyses are limited to indicators of carbon footprint or global warming potential.

Some of the studies quoted above describe a lack of quantitative data specific to this equipment, because data is kept secret by certain companies or is not communicated to the different parties involved in the supply chain. As this lack of complete data often limits the development of quantitative assessments, the data must be available before running a case study.

A quantitative assessment of the potential benefits of implementing ecodesign measures in products requires the use of complete, valid, timely and accurate data. A survey of the literature revealed that the information about the BoM, and the reuse and recycling of enterprise servers and their components, is generally scattered and treated separately by different reports.

3.4. Survey on environmental criteria for enterprise servers

Potential environmental criteria for servers are currently being discussed in the framework of the environmental leadership standard in the USA (NSF International 2015). The development of this standard is led by NSF International, which aims to establish environmental performance criteria and corporate performance metrics to give market recognition to products and brand manufacturers, and help purchasers identify environmentally preferable products. This standard includes multiple attributes and environmental performance categories, including: energy efficiency; management of substances; use of preferable materials; product packaging; design for repair, reuse, and recycling; product longevity; responsible end-of-service/end-of-life management; LCAs; and corporate responsibility. In this section, we limit the discussion to design for repair, reuse, and recycling, and product longevity.

For design for repair, reuse and recycling, the NSF draft includes the criteria of easy and non-destructive removal of external enclosures, and accessibility of components that require special handling and other relevant components (i.e. memory cards, processors, power supply, fans, etc.). Wires and cables should also be removable by hand or with commonly available tools. Another criterion discussed is the provision of “information and reporting in preparation for reuse and recycling”. Such information should be available without restriction in websites for a minimum of seven years following the end of production of the server, and in any region or country where this criterion is declared. The information to be included in manuals includes indications as to the location of various components, the specific format of manuals to ensure access to third parties, and the availability of necessary testing software for the testing of hardware functionality. It is also required that operators preparing servers for reuse are informed about the availability of information for the preparation for reuse and recycling. An optional criterion under the design for repair, reuse and recycling category is the reporting of the magnet type and location in HDDs by a QR code located in the external enclosure of the device.

Regarding product longevity, the standard proposes that product replacement components shall be available through the manufacturer or an authorised third party for at least five years after the product is first placed on the market. Among the components likely to be replaced are power supplies, fans, HDDs, memory devices, processors and other PCBs.

Table 9. Criteria included in the latest draft environmental leadership standards for servers (NSF International 2015).

<table>
<tr><th colspan="2">Design for repair, reuse and recycling</th></tr>
<tr><th colspan="2">Prerequisites</th></tr>
<tr><td rowspan="4">Design for repair, reuse and recycling</td><td>External enclosures shall be removable by hand or with commonly available tools, without destruction of the enclosure</td></tr>
<tr><td>Components with special handling needs listed in the European WEEE Directive 2012/19/EU Annex VII shall be identified, accessible, and removable by hand or with commonly available tools</td></tr>
<tr><td>At a minimum, if present in the product, data drives or cards, processor, memory DIMMs, power supply, fans and I/O cards, shall be accessible and replaceable by hand or with commonly available tools</td></tr>
<tr><td>Wires and cables that connect to external sources of power or data shall be removable from the products by hand or with commonly available tools without either the wire or cable, or the product being rendered unusable, unless required for technical or safety reasons</td></tr>
<tr><td rowspan="2">Information and reporting in preparation for reuse and recycling</td><td>The manufacturer shall publish a manual for third-party reuse and recycling organizations, in at least English, with the information listed below, including the same information as provided by the manufacturer for use by its technicians for the same purposes as follows:
- Manual shall be available on a publicly accessible website without restriction of access. The manufacturer shall declare the URL of the public disclosure.
- The manual shall be available in any region or country in which the criterion is declared and the manufacturer shall have a written procedure that makes the manual publicly available for a minimum of 7 years following the end of production of the product.</td></tr>
<tr><td>The manual shall contain the following information about preparation for reuse and recycling:
- The different components and materials; and
- The location of materials with special handling needs as identified in European WEEE Directive 2012/19/EU Annex VII ; and
- Technical reference of each individual sub-assembly providing 1) a pin diagram, and 2) the make and model of each connector capable of being field terminated, as provided to manufacturer repair/authorized service centers; and
- The components that cannot be replaced by non-manufacturer supplied components; and
- A list, updated at least annually, of any components provided by the manufacturer that are compatible or equivalent with original components; and
- A disassembly or end-of-life characterization report that demonstrates conformity to all the prerequisites in Section 9.1 and includes, at a minimum, step-by-step disassembly instructions with required tools, product specifications and troubleshooting information.</td></tr>
</table>

Design for repair, reuse and recycling	
Prerequisites	
Information and reporting in preparation for reuse and recycling (continuation)	The function specified in the manufacturer's user manual, repair manual or technical manual should be used to determine original intended function, and to assist with the preparation for reuse or treatment operations. The manual shall meet the following formatting requirements: - Available in user-friendly formatting on the web and as downloadable PDFs for offline viewing; and - Available in machine-friendly file format: either XML or oManual/IEEE 1874 – IEEE Standard for Documentation Schema for Repair and Assembly of Electronic Devices; and Provided under an open-source license that allows redistribution and modification, such as Creative Commons (www.creativecommons.org) (CC-BY).
Functionality testing software tools	The manufacturer shall make publicly available and readily accessible, and provide access to the necessary hardware functionality testing software tools and applicable updates to ensure the product meets operating specifications and can be returned to service as provided by the manufacturer's repair/authorized service centers. Manufacturer shall also make available and provide access to any system or peripheral firmware (BIOS, etc.) and drivers for the server hardware.
	The manufacturer shall have a written procedure that makes all of these items available for a minimum of 7 years following the end of production of the product and identifies if there is a cost. The manufacturer shall declare if there will be any cost associated with the provision of the functionality testing software tool. The manufacturer shall declare the URL of the public disclosure.
Informing reuse operators and treatment operators of information available for their assistance (corporate)	Manufacturers shall inform reuse operators and treatment operators with which they, or an organization working on their behalf, have a business relationship for providing end-of-service/end-of-life management of the products declared to this standard regarding the availability of the information provided under any of the following criteria to which they declare conformance: 9.1.4, 9.3.1, and 9.5.1. The method of informing reuse operators and treatment operators shall be in writing and a record of its distribution shall be documented.
Design for repair, reuse and recycling	
Rare earth recovery and recycling	
Information and reporting on disk drive magnet type and location	The manufacturer shall indicate the type of actuator/voice coil and spindle magnets in the product's hard disk drive on the external enclosure of the hard disk drive by means of a QR code. The QR code shall link directly to the magnet type and location information on a publicly available database or the manufacturer's website in at least English. The QR code shall be printed in black on a white background if one or more of the magnets contain neodymium. The QR code shall include a non-machine readable chemical symbol (Nd). In the case that neither magnet contains neodymium, the QR code shall be printed in red on a white background. The voice coil and the spindle magnet locations in the hard disk drive shall be identified by metric measurements from the edges of the disk drive.
Product longevity	
Replacement components availability	Product replacement components and, or product service shall be made available through the manufacturer or an authorized third party for at least 5 years after the product is first placed on the market. Replacement components shall include, at a minimum, power supplies, fans, hard drives, memory devices, processors and printed circuit boards. Information regarding the availability of product replacement components and, or product service shall be publicly available on the manufacturer's website. The manufacturer shall declare the URL of the public disclosure.

The availability of manuals [12] and work instructions are critical information for repair. However, it has been observed in the literature a lack of standardization (Schaffer and Wiens 2014). The IEEE 1874: Standard for Documentation Schema for Repair and Assembly of Electronic Devices (also called "oManual" [13]) (Institute of Electrical and Electronics Engineers 2013) was developed to provide a standardized format for manuals, and their compatibility to be displayed on both computers and mobile devices. The IEEE 1874 specification is an XML-based data standard allows to create dynamic, flexible and structured manuals and publishing manuals as both user-friendly PDF/HTML and machine-friendly (Schaffer and Wiens 2014). oManual files allows for the best of both worlds: manuals that retain their ease of use, but are also easy to maintain and build upon.

Another example of criteria developed regarding the enterprise server is the Code of conduct (CoC) for energy efficiency in data centres (Joint Research Centre - Institute for Energy 2015). Such CoC is a voluntary initiative, created in response to increasing energy consumption by data centres and the need to reduce the related environmental, economic and energy supply security impacts. The CoC comes together with a best practice supplement to assist data operators in identifying and implementing measures to improve energy efficiency in their data centres. Best practices are defined for entire data centre, new software, new IT equipment, new build or retrofit and optional practices. As already mentioned, although the CoC is mainly designed to improve energy efficiency, it also includes some aspects related to the environment (see table 10).

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[12] Different types of manuals are possible, including: fit for work instructions, assembly manuals, instruction manuals, user manuals, owner's manuals, how—to manuals, survival guides, and service manuals (Schaffer and Wiens, 2014)

[13] http://www.omanual.org/

Table 10. Best practices for data centres related to material efficiency (Joint Research Centre - Institute for Energy 2015).

No	Name	Description	Expected
Data centre utilization, management and planning / involvement of organizational groups			
3.2.1.	Consider the Embodied environmental impact of installed devices	Carry out an audit of existing equipment to maximise any unused existing capability by ensuring that all areas of optimisation, consolidation and aggregation are identified prior to new material investment. The most important element to this in terms of impact is the IT equipment. The severity of impact is related to the frequency of refresh and replacement.	Entire data centre
3.2.4.	Life cycle assessment	Introduce a plan for Life Cycle Assessment (LCA) in accordance with emerging EU guidelines and internationally standardised methodologies. An example of which would be ISO 14040.EN 15978 'Sustainability of construction works - assessment of environmental performance of buildings - calculation method' is also a standard that is considered relevant to this Practice. Note this Practice aims to reduce overall carbon footprint rather than direct energy efficiency.	Optional
3.2.5	Environmental management	Introduce a plan for Environmental Management in accordance with emerging EU guidelines and internationally standardised methodologies. An example of which would be ISO 14001	Optional
3.2.7	Asset management	Ensure that Asset Management for both IT and mechanical and electrical assets etc. is implemented and controlled according to a standard and accepted methodology. An example of which would be ISO 55000. Understanding the numbers, types and purposes of the assets deployed in a data centre underpins effective energy management.	Optional
Cooling. Air flow management and design			
5.1.12	Separate environmental zones	Where a data centre houses both IT equipment compliant with the extended range of Practice 4.1.3 and other equipment which requires more restrictive temperature or humidity control as described in Practice 4.1.2, separate areas should be provided. These areas should have separate environmental controls and may use separate cooling systems to facilitate optimisation of the cooling efficiency of each zone. Examples are equipment which; • Requires tighter environmental controls to maintain battery capacity and lifetime such as UPS •Requires tighter environmental controls to meet archival criteria such as tape • Requires tighter environmental controls to meet long warranty durations (10+ year) The objective of this Practice is to avoid the need to set the data centre cooling plant for the equipment with the most restrictive environmental range and therefore compromising the efficiency of the entire data centre.	New build or retrofit

4. Environmental analysis for enterprise servers

4.1. Description of an example enterprise server

The server analysed is the representative model defined in the preparatory study of Lot 9 (BIO Intelligence Service and Fraunhofer IZM 2015). Table 11 gives a technical description of the enterprise server analysed, including the manufacturing year, the number of some parts, the power consumption, the use pattern, the lifetime and the overall mass. The server being analysed is estimated to have been manufactured in 2012. The description includes the number of some parts, namely the central processing unit (CPU), fans, hard disk drives (HDDs) and power supply units (PSUs), as their number varies depending on the configuration of the server. Regarding the power consumption, details are given as to the yearly energy consumption, the use pattern and the lifetime of the server.

Table 11. Technical description of the server analysed (BIO Intelligence Service and Fraunhofer IZM 2015).

	Technical description
Manufacturing year	2012
Number of central processing units (# CPUs)	2 CPU socket (Intel E5-26XX), typical configuration according to SERT (average 2.3 GHz)
Number of fans (# Fans)	4 (4-5 watt at 25-50% load and 12-15 Watt per fan at maximum load or higher temperatures (30ºC)
Number of hard disk drives (# HDDs)	4
Number of power supply units (# PSUs)	2 x 400 W (AC/DC)
Power consumption according to SERT	idle: 150W / 25% Load 200W
Power consumption/year	1 661 kWh
Use	5h@idle + 19h@25%load * 365 days
Lifetime	4 years
Infrastructure Overhead	Power usage effectiveness (PUE): 2.0
Overall mass	27.8 kg

Table 12 shows the bill of materials (BoM) of the server studied in the later sections. The mass of each component is the same as those of the one estimated by the preparatory study Lot 9. The material composition of chassis, optical disk drive (ODD), cables and heat pipes is also provided in the preparatory study of Lot 9.

However, the composition of other parts (main board, HDDs, fans, power supply) does not include a detailed breakdown of materials, especially for micro components and electronic packages contained in PCBs. Detailed data are crucial to estimate the content of critical raw materials (CRM) in servers, perform a LCA, and calculate resource-efficiency indicators. For these reasons, information from the preparatory study has been complemented with an analysis of two servers that were dismantled at the JRC-IES (Table 13).

Moreover, during the disassembly of servers it was observed that batteries are always used as a back-up power supply in the event of PSU failure. Therefore we complemented the BoM with two batteries: a coin cell lithium battery (CR2032) and a prismatic lithium ion battery. Overall, the total mass of the server came to 27.8 kg.

Table 12. Bill of materials (BoM) of an example rack server.

Component	Material	Mass (g)	Component	Material	Mass (g)
Chassis	Steel	12 265	Main board	Controller Board	1 667
	Plastics (ABS)	348			
	Plastics (PC)	282	2 PSUs	*See table 3**	3 426
	Aluminium	249	Expansion card/ other	PCB	349
	Copper	179	Cables	Brass	7
	PCB	131		Copper	81
4 Fans	*See table 3**	946		Zinc	96
4 HDDs	*See table 3**	1 748		Plastics (HDPE)	104
ODD	Low alloyed steel	115		Plastics (PVC)	145
	Copper	7		PUR	2
	Aluminium	1		Synthetic rubber	35
	Plastics (HDPE)	28	2 CPUs	*	54
	Plastics (ABS)	12	Heat Pipes for CPUs	Low alloyed steel	140
	Plastics (PC)	7		Copper	442
	PCB	19	Memory	PCB	135
			Packaging	Cardboard	3 629
Batteries	CR2032 (button)*	1.6		Plastics (HDPE & other)	78
	Lithium ion (prismatic)*	43		Plastics (GPPS/ Styrofoam)	1 026
TOTAL: 27,799 g					

* Primary data from the disassembly of servers by the JRC-IES. ABS: acrylonitrile-butadiene-styrene; PC: polycarbonate; HDPE: High density polyethylene; PUR: Polyurethane; PVC: polyvinyl chloride.

Table 13. Primary data of typical fans, HDDs and PSU obtained from JRC-IES analyses.

Component	Materials/Components	Mass (%)	Component	Materials/Components	Mass (%)
Fan	Steel	40.8	PSU	Steel	39.3
	Copper	8.2		Aluminium	6.6
	Iron based	5.8		Fan[1]	4.5
	Plastic (PBT-GF30)	21.8		Plastic (EVA)	2.2
	Plastic (PCABSFR40)	2.2		Plastic (PCFR40)	1.5
	Plastic (undefined)	21.1		PCB	45
				Cables	0.9
Component	**Materials/Components**	**Mass (%)**	**Materials/Components**		**Mass (%)**
HDD	Aluminum	45.0	Magnet		3.9
	Steel	31.3	PCB		3.9
	Ferrous based	8.7	Plastic (PCABS)		3.9
	Copper	0.4	Plastic (PCGF)		3.0

[1] The material composition is the same as that already included under 'Fan' in this table. EVA: Ethylene-vinyl acetate; PBT: polybutyl terephthalate; PCABS: polycarbonate acrylonitrile; PCABSFR40: polycarbonate acrylonitrile containing flame retardant; PCFR40: polycarbonate containing flame retardant.

4.2. Physical architecture of enterprise servers

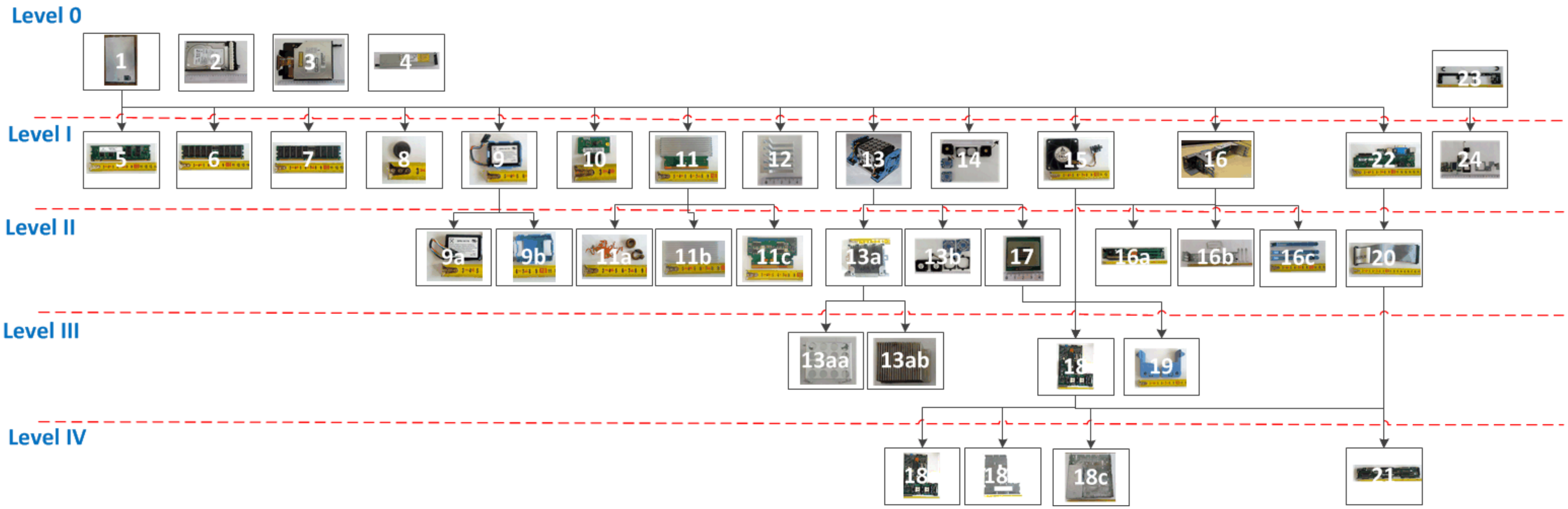
During the development of the project, several servers similar to the rack server selected for the preparatory study for Ecodesign Lot 9 were dismantled at the JRC-IES. This disassembly exercise helped to better understand the modularity of the product and the potential difficulties for reuse and recycling. A first conclusion is that enterprise servers generally have a modular design, which allows for the easy replacement of most of their components during their lifespan.

Figure 11 shows the modularity of a typical rack server, as observed during disassembly of servers at the JRC-IES premises. As illustrated, several components, namely the HDD (2), the ODD (3) and the PSU (4) can be extracted from the server without having to remove any additional component. This design facilitates the separation of these components, which benefits maintenance, upgrades, and the reuse and selective treatment and recycling of parts. Further steps are needed to harvest potentially valuable parts from those components, such as for instance PCBs in HDDs and ODDs, and magnets in HDDs.

Removing the top cover (1) of the server grants access to the interior and thus to the remaining components. There are several components that can be readily extracted: memory cards (5-7), coin cell battery (8), fans (14-15) and some other PCBs (10; 22). In order to extract other components such as the expansion card (16a), a metallic shell (16b) and some plastic levers (16c) need to be removed. Similar steps are needed to separate lithium ion prismatic batteries (9a) embedded in a plastic shell (9b), and fans (14). The processor (CPU) (17) can be only extracted once the heat sinks (13a) and fans (13b) are removed. The main board (18a) is accessible once the processor (17), heat sink (13a) and fans (13b) are taken out. As it is normally screwed to a metal sheet (18b), additional steps are needed to separate it.

The main board contains many components that can be further separated, such as smaller heat sinks that are glued to additional processors, CPU sockets, memory card slots, capacitors, connectors, etc.

From a resource-efficiency perspective, the separation of some parts can be relevant since some material combinations and mixtures might not be compatible for recycling (see figure 14). For example, if the main board is recycled in a copper smelter, all aluminium and steel in other parts included in the main board would be lost. The preventive extraction of some parts such as metal sheets and heat sinks would be more beneficial, as it would minimise potential losses of valuable metals.



Description of the parts included in the figure:
1: Cover; 2: Hard disk drive (HDD); 3: Optical disk drives (ODDs); 4: Power supply unit (PSU); 5-7: Memory cards; 8: coin cell battery; 9: Li ion prismatic battery pack; 9a: Li ion battery; 9b: Li ion plastic shell; 10: Raid card; 11: VRM card for CPU; 11a: Copper coils; 11b: Heat sink; 11c: PCB for VRM card; 12: Heat sink; 13: Heat sink set for CPU; 13a: Heat sink; 13b: Fans for CPU; 14: Fans for the back of the server; 15: Fan for expansion card; 16: Expansion card bay; 16a: Expansion card; 16b: Expansion card shell; 16c: Levers for expansion card shell; 17: CPU; 18: Main board set; 18a: Main board; 18b: Main board support sheet; 18c: chassis; 19: Levers for main board; 20: Cable; 21: PCB to connect HDD to Main board; 22: PCB in Chassis; 23: Front of server; 24: PCB in chassis with small display.

Figure 11. Disassembly sequence of a rack enterprise server.

4.3. Estimate of critical raw materials in servers

The term critical raw materials (CRM) gained particular importance from 2010 onwards, when several reports on the subject were published (European Commission 2010; US Department of Energy 2011). Since then, literature has mainly concentrated on understanding the sources of these materials and possible supply restrictions. Other publications partially analyse their functionalities and end-uses where these materials are stocked (Buchert, Schueler et al. 2009; Du and Graedel 2011; Du and Graedel 2011; Erdmann and Graedel 2011; Ayres and Talens Peiró 2013; Reuter, Hudson et al. 2013; Talens Peiró, Villalba Méndez et al. 2013). Although some papers also discuss their possible content in some products, for some parts (especially PCBs) this is hard to estimate as they are normally customised based on clients' requests. For instance, the composition of PCBs that perform the same function in a product can be different.

Traditionally, the presence of CRM and other valuable metals (copper and Platinum Group Metals - PGMs) has been estimated based on chemical analysis. In most cases, PCB samples are taken from recycling sites, and have different origins. This means that complete data as to the composition of each material/substance is even harder to obtain. In fact, currently available studies that estimate the content of CRM and other valuable metals use average compositional data for products or even a mix of PCBs without taking into account their functionality in products. Table 14 illustrates the average content of CRM in parts contained in e-waste.

Table 14. Content of critical raw materials (CRM) in electronic waste.

Part	Material	Symbol	Content
Batteries	Cobalt	Co	Mean content in mixed lithium-ion battery packs (in mass) 13.8% (Buchert, Manhart et al., 2012)
	Lithium	Li	Content in button/coin batteries 0.05-0.10 g Content in prismatic secondary batteries 0.30-3.10 g (Talens Peiró, Villalba Méndez et al. 2013)
HDD	Dysprosium	Dy	Average content in magnets (in mass): 20% Nd; 5% Pr; 5% Dy; 1% Tb (Du and Graedel 2011) Content in HDD (in mass): 60 mg Dy; 1,044 mg Nd; 145 mg Pr (Buchert, Manhart et al. 2012)

Part	Material	Symbol	Content
PCBs	Palladium	Pd	Poor PCB: 10-100 [mg/kg]; Rich PCB: 100-470 [mg/kg] (Reuter, Hudson et al. 2013); average content: 50-2200 ppm (Duan, Hou et al. 2011)
	Platinum	Pt	Rich PCB: 7- 40 [mg/kg] (Reuter, Hudson et al. 2013); average content: 4.6-30 ppm (Duan, Hou et al. 2011)
	Antimony	Sb	Average content (in mass): 0.4-20 ppm (Khaliq, Rhamdhani et al. 2014); Average content (in mass) in: main board (0.06%); average PCB (0.4%) (Duan, Hou et al. 2011)
	Silicon	Si	Content of SiO_2 in various PCB: 15-24.7% (in mass)(Duan, Hou et al. 2011) average content: 15-41.86% (Khaliq, Rhamdhani et al. 2014)
	Gallium	Ga	Content in average PCB: 13 ppm [Ewasteguide.info, 2014]
	Germanium	Ge	Content in average PCB: 16 ppm [Ewasteguide.info, 2014]
	Cobalt	Co	Average content in computer PCB: 12 [mg/kg] (Hall and Williams 2007); content in mixed PCB: 4000 ppm (Yoo, Jeong et al. 2009)

HDDs: hard disk drives, PCBs: printed circuit boards

As shown in Table 14, there is a large variability in the content of CRM, especially in PCBs. In this analysis, we have used a bottom-up approach to estimate the material composition of PCBs. First, we dismantled several enterprise servers and harvested the different PCBs they contained. This exercise also proved useful to understand the difficulties in reaching these valuable parts. Secondly, the mass, dimension and location of each of the PCBs in the server was described. The mass of PCBs ranged from 19 to 1 667 grams, whereas the dimensions ranged from 18 to 1 680 cm^2. A more detailed analysis was carried out to list the type, mass and dimension of components (mainly packages and capacitors), and the number of layers of the boards. The content of CRM and other metals was then estimated based on the material declarations of the manufacturers. Due to data availability, most of the effort was concentrated on integrated circuits, capacitors, transistors and coils (see figure 15 in section 4.5.3).

Table 15 summarises the amount of CRM in the various components, including PCBs. The amount of some CRM listed in table 14, namely platinum, antimony, gallium, germanium and cobalt, are not included because they were not declared in the FMD of the packages analysed.

There are several possible reasons for the absence of these materials in the PCBs analysed. First, they might be used in components that are not mapped in this study. Second, some of the information included in table 15 is from other products manufactured about a decade earlier. Therefore, technological changes may have influenced the composition of the packages analysed, and as a result some of the materials were not used when the PCBs were manufactured for the server. Table 16 gives the overall estimate of CRM in rack servers.

Table 15. Critical raw materials in PCBs included in enterprise servers.

Part	Material	Symbol	Content	Amount per server (g)
Batteries	Cobalt	Co	Li polymer battery (Ansmman, 2011): 5.1783-12.9457 g	9.0620
	Lithium [a]	Li	Coin battery (CR2032): 0.07g (Maxell,2015) Li polymer (Ansmman, 2011): 0.6098 – 1.5246 g	1.1372
HDD	Dysprosium	Dy	Average content in magnets (in mass): 21.2% Nd; 5.3% Pr; 5.3% Dy; 1.1% Tb (Du and Graedel 2011)	3.6040
	Neodymium	Nd		14.4160
	Praseodymium	Pr		3.6040
	Terbium	Tb		*0.7480*
PCBs [b]	Magnesium	Mg	Chassis: 0.0001g; Expansion card : 0.0004g; Mainboard: 0.0024g; HDD: 0.011g;	0.0040
	Neodymium	Nd	Chassis: 0.0011g; Expansion card: 0.0217g; Memory card: 0.0115g; Mainboard: 0.1354g; HDD: 0.0438g	0.2135
	Palladium	Pd	Chassis: 0.0157g; Expansion card: 0.0389g; Memory card: 0.0207g; Mainboard: 0.2432g; HDD: 0.0786g	0.3971
	Silicon [c]	*Si*	*Chassis: 0.2408g; ODD: 0.0045g; Expansion card: 0.5238g; CPU: 0.0950g; Memory card: 3.7930g; Mainboard: 1.5492g; HDD: 0.4480g*	*6.6544*
Connectors [b]	Antimony	Sb	4.4447 g	4.4361
	Beryllium	Be	0.0348 g	0.0348
	Chromium	Cr	8.5648 g	8.5648
	Cobalt	Co	0.2039 g	0.2039
	Palladium	Pd	0.0002 g	0.0002
	Silicon [d]	Si	4.5726 g	4.5726

[a] Lithium is excluded from the CRM in 2014 [b] Data sources used to estimate the content of CRM are included in table A4 in the annex of this report [c] Silicon in servers is contained in electronic grade (9N) in the die of packages [d] In most cases silicon is contained in stainless steel alloys

Table 16. Estimated amount of critical raw materials in enterprise servers

Material	Symbol	Amount per server (g)	Material	Symbol	Amount per server (g)
Antimony	Sb	4.4361	Silicon [b]	Si	11.2271
Beryllium	Be	0.0348	Rare earth elements (REEs)		
Chromium	Cr	8.5648	Material	Symbol	Amount per server (g)
Cobalt	Co	9.2659	Dysprosium	Dy	3.6040
Lithium [a]	Li	1.1372	Neodymium	Nd	14.6295
Magnesium	Mg	0.0040	Praseodymium	Pr	3.6040
Palladium	Pd	0.3973	Terbium	Tb	0.7480

[a] Lithium is excluded from the CRM in 2014 [b] Silicon in servers is contained different grades: electronic grade (9N) in the die of packages, and in stainless steel alloys

In conclusion, CRM in servers are located in batteries, HDDs, PCBs and connectors. The CRM contained in greatest amounts is Neodymium in the magnets of HDDs, followed by silicon in the die of integrated circuits, and cobalt in batteries. There are various recycling approaches to recover sintered neodymium magnets, most of which are tested under ideal conditions in laboratories (Schueler, Buchert et al. 2011; Binnemans, Jones et al. 2013; Sprecher, Xiao et al. 2014; Zakotnik and Tudor 2014). These approaches include waste-to-alloy, hydro-metallurgical, pyro-metallurgical, and a magnet-to-magnet method developed by Zakotnik et al., which have been shown to work at the commercial scale (Zakotnik, Williams et al. 2008). The cobalt contained in lithium batteries is currently recycled at the commercial scale (Dewulf, Van der Vorst et al. 2010). Research on recycling silicon is mostly carried out during the manufacture of silicon wafers; further research on how to recover silicon from dies may be carried out if silicon is classified as a critical raw material.

4.4. Estimate of hazardous substances in servers

Hazardous substances are solids, liquids or gases that are often subject to regulations due their potential to harm living organisms and/or the environment. Products containing regulated and restricted substances must follow specific treatments not only during their production and use, but also at their end-of-life, in order to reduce their potential environmental impact. At present, several regulations provide a list of hazardous substances (European Parliament and of the Council 2003; European Parliament and of the Council 2006; European Commission 2011). The Restriction of Hazardous Substances (RoHS) Directive refers to the presence of cadmium (Cd), hexavalent chromium (Cr VI), lead (Pb), mercury (Hg), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). In addition, 161 substances are listed as Substances of Very High Concern (SVHC) by the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) of December 2014.

Enterprise server, as some other electrical and electronic equipment concentrates most of these substances in PCBs. PCBs contain substances such as arsenic, antimony, beryllium, brominated flame retardants, cadmium and lead. Capacitors are also important due to their potential content of cadmium, mercury and polychlororbiphenyl (Eco-systèmes and Terra 2012).

Concerning the lead, the RoHS Directive exempted the application of ‘lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunications’.

4.5. Life cycle assessment of an enterprise server

4.5.1. Goal and scope of the study

The overall aim of the study is to assess the potential environmental impact of a rack-optimised enterprise server. One of the objectives is to determine environmental hotspots during the product’s life cycle, with a specific focus on the manufacturing of components and materials and its end of life. It is expected that the results will help identify possible measures to improve the resource efficiency of enterprise servers. For the environmental assessment, the impact categories selected are those recommended in the International Reference Life Cycle Data (ILCD) handbook and the EU Product Environmental Footprint (PEF). In order to ensure the comparison of JRC-IES results with those from the preparatory study of enterpriser servers (Lot 9), the following impact categories are also included:

- Primary energy demand from renewable and non-renewable resources (gross cal. value) [MJ]
- IPCC global warming, excluding biogenic carbon [kg CO_2 eq.]
- CML2001 - Apr. 2013, Acidification Potential (AP) [kg SO_2 eq.]

The functional unit of the study is one enterprise server (27 799 kg in mass). The system boundaries of the study are:

i. Manufacturing of raw materials and parts
ii. Assembly of the server
iii. Transport
iv. Use phase
v. End of life

4.5.2. Data sources

This section describes the data sources used for each of the lifecycle stages of the server analysed. Data sources used for the lifecycle inventory analysis are presented in the Annex (Tables A3 and A4).

4.5.2.1.Manufacturing phase

The manufacturing of a server includes four major steps: the extraction of raw materials for the manufacturing of components, the transport of components from manufacturing sites to assembly sites, the assembly of the server, and its packaging. These stages are illustrated in figure 12.

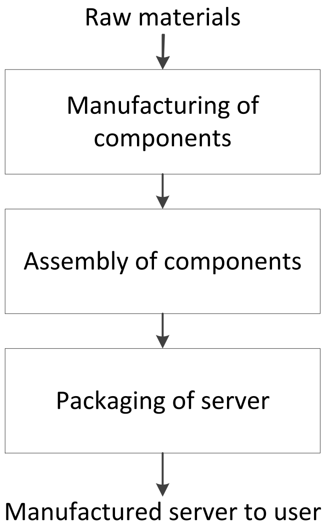


Figure 12. Steps involved in the manufacturing of a server.

Data about the manufacturing of components contained in greater amounts in servers, such as major metals and plastics, are generally readily available in most lifecycle inventories. For instance, both Ecoinvent and PE-GaBi contain inventory data for manufacturing steel, copper, aluminium from different mineral ores, manufacturing processes, and also in most cases for plants in different country locations with diverse energy mixes. By contrast, data about the manufacturing of electronic components such as HDDs and memory cards are scarce, and tend to be scattered in the scientific literature. The assessment of electronic components is highly time-consuming, especially with regard to data gathering and chemical analyses, but also because primary data becomes outdated due to rapid technological advances. LCAs for electronics published in early-mid 2000 generally refer to primary data generated about five years previously (Williams, Heller et al. 2003; Hischier, Classen et al. 2007), whereas the average time taken to launch a new electronic product in the market is about three years. The analysis of components in the semiconductor industry is further complicated by the fact that it extends globally and many companies operate internationally. Supply chains are becoming increasingly flexible, and are rapidly changing over time. The assessment of semiconductors and their related products can therefore be outdated rather quickly, even when based on primary data. In this section we describe, in as much detail as possible, the data sources and assumptions made when performing an LCA of electronic components, especially PCBs.

During the past years, several changes have influenced the supply chain of semiconductors. As manufacturing techniques became more developed and standardised, the design and manufacturing processes have been separated. One of the early dominant models was to locate research and design activities in developed economies (i.e. Japan, the EU and US) while locating manufacturing operations as component assembly in another site with low labour costs (Boyd 2009). The separation of design and manufacturing has progressed to the point that these operations are presently carried out by different companies. Companies that specialise only in the research and development of integrated circuits (ICs) are known as fabless facilities, whereas companies that fabricate and test the physical devices are called foundries. If the foundry does not have any semiconductor design capability, it is called a pure-play semiconductor foundry.

This new distribution of the supply chain for semiconductors is based on a combination of factors, including tax incentives, availability and cost of capital, access to reliable power and water supplies, and the ease of the regulatory environment (Brown and Linden 2005). This trend towards outsourcing production facilities has been driven by the increasing capital cost of wafer fabrication plants. For example, wafer fabrication and manufacturing of Intel's microprocessors and chip sets is conducted in the USA (Arizona, New Mexico, Oregon and Massachusetts), China, Ireland and Israel. Following their manufacture, the majority of the components are then assembled and tested at facilities in Malaysia, China, Costa Rica and Vietnam (Intel 2014). Figure 13 shows that over 65% of the semiconductor production capacity in 2013 was concentrated in East Asia, with Taiwan having the greatest capacity, followed by Korea and Japan.

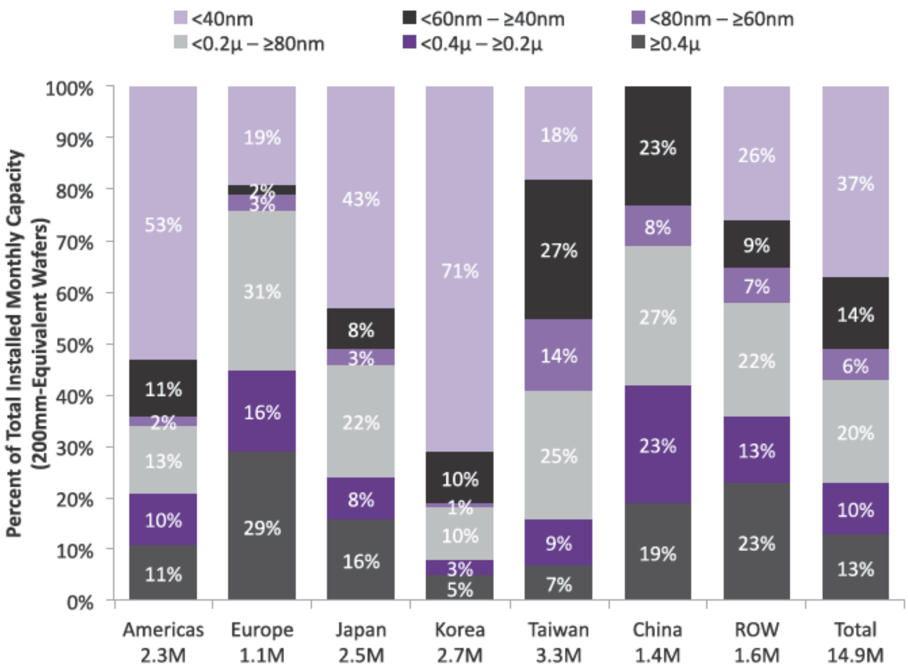


Figure 13. Installed monthly capacity of each geographic region by minimum geometry (from <40nm to ≥ 0.4μ), as of December 2013 (IC insight 2014).

In 2014, the top 20 semiconductor sales leaders included two pure-play foundries (both based in Taiwan but operating in China and Singapore) and six fabless companies (Taiwan Semiconductors Manufacturing Corporation 2014; United Microelectronics Corporation 2014). As these companies are the greatest suppliers of semiconductor components for servers, we assume that most semiconductors and parts are manufactured in East Asia. Semiconductors manufactured in East Asia are assembled with other materials to form components that will be included in servers.

There is only limited information on the technologies used to assembly diverse electronic components into bigger components and parts needed for servers. We estimated the energy used in the assembly of some components based on datasets from PE-GaBi and Ecoinvent. PE-GaBi refers to the energy used to assemble PCBs as the assembly line of surface-mount device (SMD). Data for power supplies and heat pipes for CPUs were estimated based on Hischier et al. (2007) whereas data for chassis, fans and cables were not included due to the lack of information. The packaging in which the server is sold (boxes, bags, isolating foam, etc.) is also considered as an input to the manufacturing phase (BIO Intelligence Service and Fraunhofer IZM 2014), and data for assembly are taken from PE-GaBi.

Table 17. Energy (kWh per unit) used to manufacture and assemble some components in one server.

Component	Energy for assembly (kWh)	Source
Chassis	n.a.	-
Fan	n.a.	-
Hard disk drive (HDD)	2	(Hischier, Classen et al. 2007)
Optical disk drive (ODD)	1.40	(Hischier, Classen et al. 2007)
Batteries	Incl.	(PE-GaBi, 2013)
Main board	Incl.	(PE-GaBi, 2013)
Power supply unit (PSU)	0.50	Estimate based on (Hischier, Classen et al. 2007)
Expansion card	Incl.	(PE-GaBi, 2013)
Cables	n.a.	-
Central processing unit (CPU)	Incl.	(PE-GaBi, 2013)
Heat pipes for CPU	0.10	Estimate based on (Hischier, Classen et al. 2007)
Memory cards	Incl.	(PE-GaBi, 2013)
Packaging	Incl.	(PE-GaBi, 2013)

N.a.: data not available. Incl.: data included in the inventory data as 'Assembly line SMD' in PE-GaBi dataset 2013.

4.5.2.1.1. Assembly of the server

The assembly of an enterprise server involves diverse phases: the plugging in of server components, the installation of software, and the testing of the system. The first step involves plugging various components (i.e. PSU, mainboard, processors, memory cards and HDD) into the server. Once all parts are plugged in, servers are configured by installing software. They are then tested in a laboratory to check the power, the connection to the network and the cooling systems inside the casing. Overall, the time taken to test each server is about 25-30 minutes. The energy used in assembling the components in a server and checking its operability is estimated at 6.5 kWh (OVH.com 2014).

4.5.2.1.2. Transport of the manufactured server

Based on the previous analysis, all of the server components are assumed to be manufactured, assembled and packed in East Asia (China). They are then transported by truck in China to be shipped in containers from Taiwan to Europe. Manufactured servers arrive in the North of Europe, and then are transported by truck to sites in central Europe where they are stocked.

Overall, we estimate a total travel distance of 20 500 km. Table 18 gives a breakdown of the distances estimated for the study, and the inventory data used for the assessment.

Table 18. Transport (km per unit) of an enterprise server from manufacturing site to user

Type of transport	Location	Distance (km)	Inventory
Road transport from manufacturing site	China	400	RER: Lorry (22t) incl. fuel (ELCD)
Shipping to Europe	China – Europe	19 000	EU-27: Container ship ocean incl. fuel (PE)
Road transport to storage site location	Europe	600	RER: Lorry (22t) incl. fuel (ELCD)
Road transport to user	Europe	500	

4.5.2.2.Use phase

The assumptions made for the use phase are defined by the preparatory study of enterprise servers where the use phase is defined as follows (BIO Intelligence Service and Fraunhofer IZM 2014):

- Use pattern:
  - 5h in idle mode (the server is not asleep, but no applications are running)
  - 19h at 25% load (executing tasks with a CPU load of 25%)
- Annual power consumption (according to SERT - idle: 150W / 25% Load: 200W): 1 661 kWh
- Days of active utilisation per year: 365 days
- Lifetime: 4 years
- Infrastructure Overheads: 2.0 for power usage effectiveness (PUE)[14]

4.5.2.3. End-of-life phase

One of the main objectives of the study was to define realistic EoL scenarios in order to identify relevant components and processes, identify opportunities for the reduction of environmental impacts, and propose potential Ecodesign measures to improve the resource efficiency of enterprise servers. Figure 14 summarises the various treatments to which enterprise servers are subjected once discarded by the 'first user'. Information included in this figure has mostly been gathered from original equipment manufacturers, refurbishing workshops and server recyclers.

As illustrated in figure 14, discarded servers are sent for testing, or manual or automatic separation based on their integrity and the manufacturing year of their parts. Intact servers are tested to verify whether or not they still function. If so, they can be reused as 'equivalent to new' servers. Servers that no longer function are used to harvest parts that are functioning and technologically up-to-date. Those harvested parts are stocked to be reused as spare parts

[14] Power usage effectiveness (PUE) is defined as the total facility power versus IT equipment power. PUE represents the energy consumed by supporting equipment (i.e. cooling, power supply, lighting, etc.) required for the proper functioning of the equipment.

or to build servers of an 'equal or lower' technological profile, which are still in demand by certain customers. Figure 14 describes this type of server as 'reused servers'. The parts of the server that do not function or are technologically obsolete are separated for recycling, incineration and landfill.

Damaged and technologically out-of-date servers are disassembled/separated manually and/or automatically. Parts that are likely to function are harvested manually and sent for testing. If they are still functioning, they are stocked to be reused in 'equal or lower' profile servers (figure 14 describes this type of server as 'refurbished servers'[15]). By mechanical separation, mainly based on shredding processes, different types of materials contained in the server are separated and later recovered through various recycling processes. Four major types of 'material groups' are differentiated: iron-based metals, non-iron-based metals, PCBs, and plastics. Iron-based metals are assumed to be recycled using 'steel route' pyrometallurgy, whereas non-iron-based metals are recycled either by 'aluminium', 'copper' or 'lead' pyrometallurgy processes, depending on the dominant metal in the composition mix. PCBs are generally treated using a combination of 'copper' and 'lead' pyrometallurgical processes, also depending on the content of diverse metals. Hydrometallurgical processes may follow depending on the desired grade of the metal due to be recovered (i.e. 99.99% purity Palladium). Plastics are assumed to be recycled by mechanical or chemical routes, depending on their type. Fractions of materials that have insufficient concentrations of certain compounds and for which no industrial-scale recycling processes are yet implemented are assumed to be incinerated for energy recovery, and/or landfilled.

Figure 14 summarises the three different EoL scenarios, represented by three discontinuous lines (purple, orange and red), as follows:

- **Scenario 1 (purple line):** Used servers are collected by original equipment manufacturers (OEMs) or refurbishing workshops to be partially reused and recycled. Under this scenario, servers are reused as whole units, used to harvest functional and up-to-date parts, or sent for recycling after manual and automatic separation of the remaining parts. The amount of servers following any of these possible routes varies depending also on the type of ownership. Servers that are owned by private companies tend to have a higher 'reuse' rate than those that are leased. However, the amount of servers being used to harvest parts is approximately the same for servers that are owned and those that are leased.

- **Scenario 2 (orange line):** Used servers are collected by specialised WEEE recyclers. The parts that must be treated separately according to legislation (i.e. batteries, cables, main board) or because of their content of valuable materials (CPUs, HDDs, memory and expansion cards) are separated manually from the server. The remaining parts are

[15] Refurbished servers refer to repaired servers containing replaced parts or re-assembled servers which maintain their original identity, functionality and specifications.

separated automatically by mechanical processes, including shredding. Shredded fractions are recycled in various ways depending on the materials contained and the overall composition.

- **Scenario 3 (red line):** Used servers are collected by recyclers and automatically sorted without any previous treatment. Shredded fractions are recycled in various ways depending on the materials contained and overall composition. In this study, this scenario is defined as the worst-case scenario which is unlikely to occur, as the majority of servers are taken back by OEMs and specialised workshops, and are then sent to specialised recyclers.

For Scenarios 2 and 3, the electricity used for shredding is estimated as 65.6 kWh per tonne, and the transport distance is estimated to be 200 km (Huisman 2003).

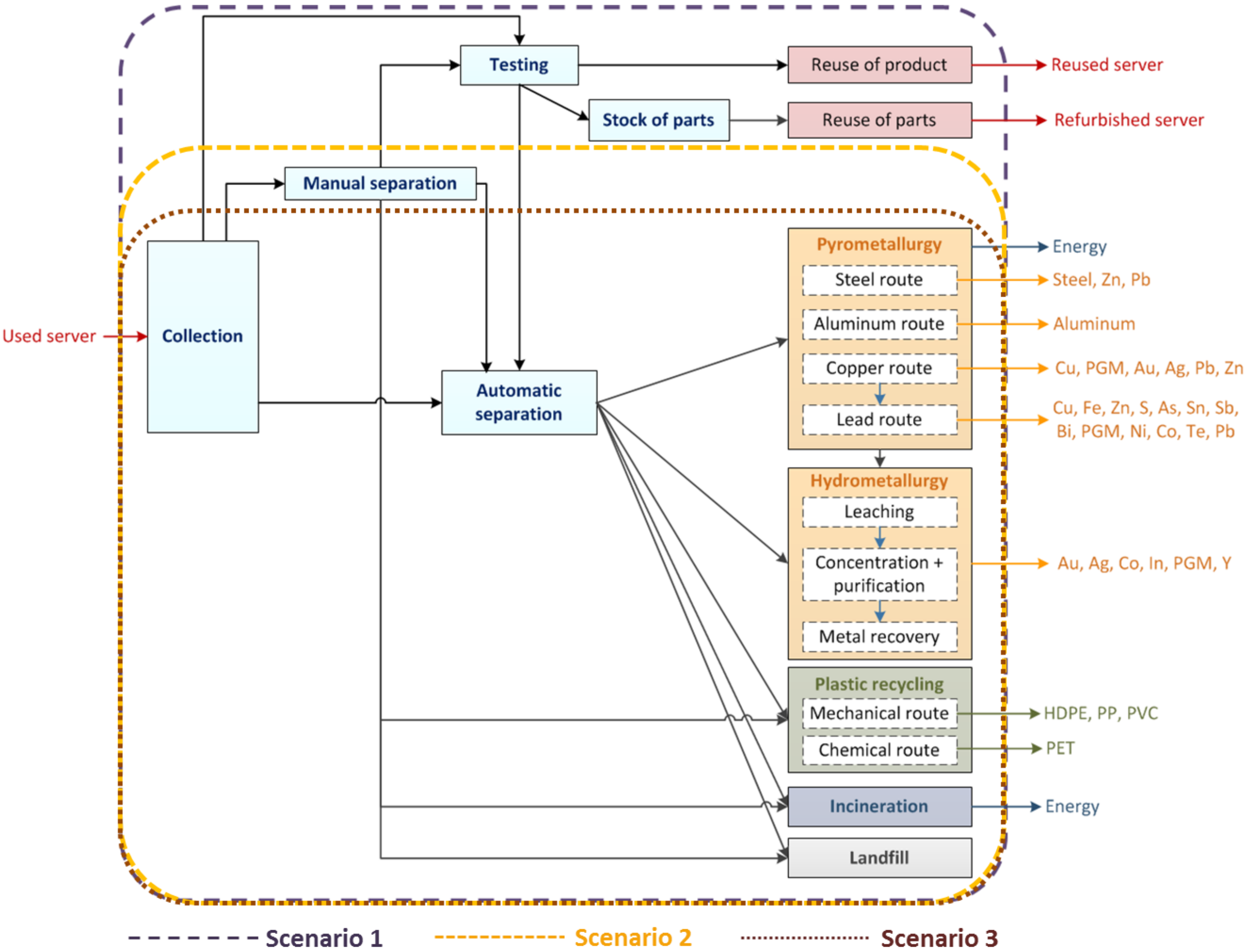


Figure 14. End-of-life of used enterprise servers once discarded by the first user.

4.5.3. Lifecycle inventory analysis

The annex includes the inventory data used for the lifecycle analysis of all components in the server, and also that for the electronic components of PCBs which required further investigation (see Annex tables A3 and A4). Both tables give the names of the materials as listed in the BoM of the server and the processes as found in the various inventory data sources. The development of the inventory analysis of PCBs is more complex. The analysis starts with a brief description of the functions, dimension, mass, and location of the PCBs in servers. Table 19 summarises the results for some PCBs found in one server, giving the sum of the size and mass of the different PCBs found in chassis, ODDs and PSUs.

Table 19. Description of PCBs contained in a representative enterprise server.

Location of PCB	Main function	Dimension (m^2)	Mass (kg)
Chassis	Provide connectivity and output information about the functioning of the server	0.040	0.329
HDD	Support drive's operations (the chips mounted include one that contains firmware with a number of drive-specific attributes such as voice coil voltage, spindle speed, head-to-head relation (HHR) and other information) and connect the drive to another device	0.010	0.032
ODD	Provide power connectivity, control spindle motor and operations	0.005	0.015
Mainboard	Perform operations	0.168	1.580
PSU	Maintain a voltage within a specified range while supplying sufficient current	0.036	0.742
Expansion card	Add functionality to a computer system via the expansion bus which moves information between the internal hardware of a computer system (including the CPU and memory card) and peripheral devices	0.022	0.286
Memory cards	Store information	0.003	0.022

A more detailed analysis is then carried out to identify and list the type and number of the electronic components mounted in each PCB. Figure 15 gives an example of the electronic components found in the front and back of one of the PCBs contained in an optical disk drive (ODD). Among the components found in the front side are coil miniature wounds, capacitors, transistors and various types of integrated circuits (ICs). The reverse side is populated by various ICs, and small ceramic capacitors.

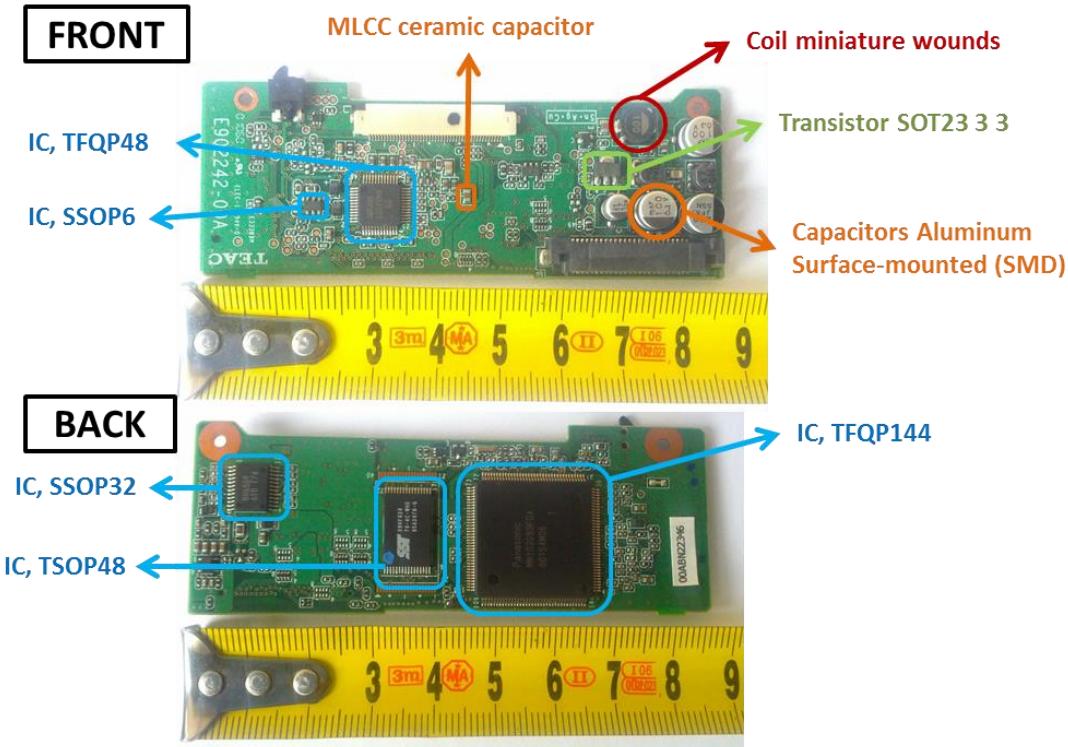


Figure 15. Front and back of a printed circuit board found in an optical disk drive.

The inventory analysis presented in Figure 15 is made of all PCBs contained in the server. Developing such detailed analyses allows for a more accurate assessment of the potential environmental impact of different PCBs, and also allows for a better quantification of the materials contained, and thus the potential amounts to be recycled, without having to perform an individual and detailed chemical analysis of each of the PCBs found in the server.

Once the components contained in the PCBs are listed, their potential environmental impact can be modelled by using an extension database for electronics developed by PE-GaBi (PE-GaBi 2013). Table A4 in the Annex lists the inventory data used for the components included in the assessment, and describes the electronic components found in the PCBs, including their dimensions (as it is difficult to estimate their mass). The table gives the names of the processes as displayed in the PE-GaBi database to model the LCA, and the document used to quantify the content of some valuable and critical raw materials. The dimensions of some components are approximated when not available from primary sources.

4.5.4. Lifecycle impact assessment

The potential environmental impact of enterprise servers was calculated based on data sources (section 4.5.2) and inventory analysis (section 4.5.4). The impact assessment focuses on the recycling of the server at its end-of-life (EoL) (scenarios 2 and 3). The analysis of reuse (scenario 1) is discussed in section 4.6.1. In scenario 2, servers are collected parts that must undergo selective treatments due to legislation (i.e. batteries, cables, main board) or because of their content of valuable materials (CPU, HDD, memory and expansion cards) are manually separated. The remaining components are separated automatically using different mechanical processes, including shredding. In scenario 3, servers are sorted and directly shredded, and then recycled in different ways. The potential environmental impacts of scenario 2 are listed in table 20, whereas those of scenario 3 are listed in table 21.

Table 20. Potential environmental impact of an enterprise server (EoL scenario 2)

Environmental impact categories	LCA of a server			
	Manuf.	Use	EoL	Units
Impacts ILCD/PEF Recommendation				
Ecotoxicity for aquatic fresh water, USEtox	1003.46	93.38	-732.10	CTUe
Freshwater eutrophication, EUTREND model	2.58E-02	3.93E-03	-1.94E-02	kg P eq
Human toxicity cancer effects, USEtox	1.71E-05	2.69E-06	-2.98E-06	CTUh
Human toxicity non-canc. effects, USEtox	8.38E-05	7.58E-05	-2.28E-05	CTUh
IPCC global warming, excl. biogenic carbon	918.80	3133.69	-58.82	kg CO_2-eq
IPCC global warming, incl. biogenic carbon	922.16	3124.31	-54.14	kg CO_2-eq
Marine eutrophication, EUTREND model, ReCiPe	4.44E-02	1.37E-01	-4.78E-03	kg N-eq.
Ozone depletion, WMO model, ReCiPe	7.00E-06	2.33E-06	-3.48E-06	kg CFC-11 eq
Particulate matter/Respiratory inorganics, RiskPoll	5.71E-01	1.07E+00	-1.31E-01	kg PM2,5-eq
Photochemical ozone formation, LOTOS-EUROS model, ReCiPe	3.41E+00	6.51E+00	-4.71E-01	kg NMVOC
Terrestrial eutrophication, accumulated exceedance	12.49	22.85	-1.53	Mole of N eq
Total freshwater consumption, including rainwater, Swiss Ecoscarcity	538.23	3279.42	-31.60	UBP
CML 2001 - April 2013				
Abiotic Depletion (ADP elements)	1.05E-01	5.48E-04	-6.67E-02	kg Sb-Eq
Acidification Potential (AP)	5.88	15.73	-2.14	kg SO2-Eq
Primary energy				
Primary energy demand (gross cal. value)	1.30E+04	7.06E+04	-6.96E+02	MJ

Table 21. Potential environmental impact of an enterprise server (EoL scenario 3)

Environmental impact categories	LCA of a server			
Impacts ILCD/PEF Recommendation	Manuf.	Use	EoL 3	Units
Ecotoxicity for aquatic fresh water, USEtox	1003.46	93.38	-222.51	CTUe
Freshwater eutrophication, EUTREND model	2.58E-02	3.93E-03	-5.44E-03	kg P eq
Human toxicity cancer effects, USEtox	1.71E-05	2.69E-06	-1.79E-06	CTUh
Human toxicity non-canc. effects, USEtox	8.38E-05	7.58E-05	-8.46E-06	CTUh
IPCC global warming, excl. biogenic carbon	918.80	3133.69	-49.15	kg CO_2-eq
IPCC global warming, incl. biogenic carbon	922.16	3124.31	-44.52	kg CO_2-eq
Marine eutrophication, EUTREND model, ReCiPe	4.44E-02	1.37E-01	-1.54E-03	kg N-eq.
Ozone depletion, WMO model, ReCiPe	7.00E-06	2.33E-06	-3.11E-06	kg CFC-11eq
Particulate matter/Respiratory inorganics, RiskPoll	5.71E-01	1.07E+00	-6.16E-02	kg PM2,5-eq
Photochemical ozone formation, LOTOS-EUROS model, ReCiPe	3.41E+00	6.51E+00	-2.56E-01	kg NMVOC
Terrestrial eutrophication, accumulated exceedance	12.49	22.85	-0.82	Mole of N eq
Total freshwater consumption, including rainwater, Swiss Ecoscarcity	538.23	3279.42	-17.21	UBP
CML 2001 - April 2013				
Abiotic Depletion (ADP elements)	1.05E-01	5.48E-04	-2.24E-02	kg Sb-Eq
Acidification Potential (AP)	5.88	15.73	-0.87	kg SO2-Eq
Primary energy				
Primary energy demand (gross cal. value)	1.30E+04	7.06E+04	-4.90E+02	MJ

A first conclusion is that all the results for the environmental impact categories for both EoL scenarios are negative. This means that, in both cases, the recycling of the server helps reduce the potential environmental impact over its complete lifecycle. A more in-depth analysis of the results for the EoL scenarios shows that the potential savings due to recycling as in scenario 2 are for 5 out of 16 impact categories three times than of scenario 3 and, for 7 out of 16 impact categories, twice the savings of scenario 3. For example, the potential savings in terms of abiotic depletion potential for elements (ADP elements) under scenario 2 is three times greater than under scenario 3. For other impact categories, such as global warming potential, primary energy demand and ozone depletion (ODP), the results do not vary much.

A second observation is that the manufacturing phase has a greater environmental impact on some categories, whereas the use phase has a greater impact on others. Environmental impact categories, such as for instance global warming potential, which is heavily dominated by electricity consumption, are more impacted during the use phase, whereas categories affected by the use of resources, such as abiotic depletion potential, are more impacted during the manufacturing phase.

For material efficiency, one of the most relevant impact category is the "Abiotic depletion potential – elements" (ADP_{el}). As illustrated in Figure 16, the potential savings to be made by recycling using the processes included in scenario 2 are over 60%, whereas for scenario 3 they are about 20%. Most of the higher potential savings under scenario 2 is due to the higher recovery rates of metals in small amounts such as gold, palladium and silver, whose recycling rates vary from 26% to almost 99% for metals such as silver.

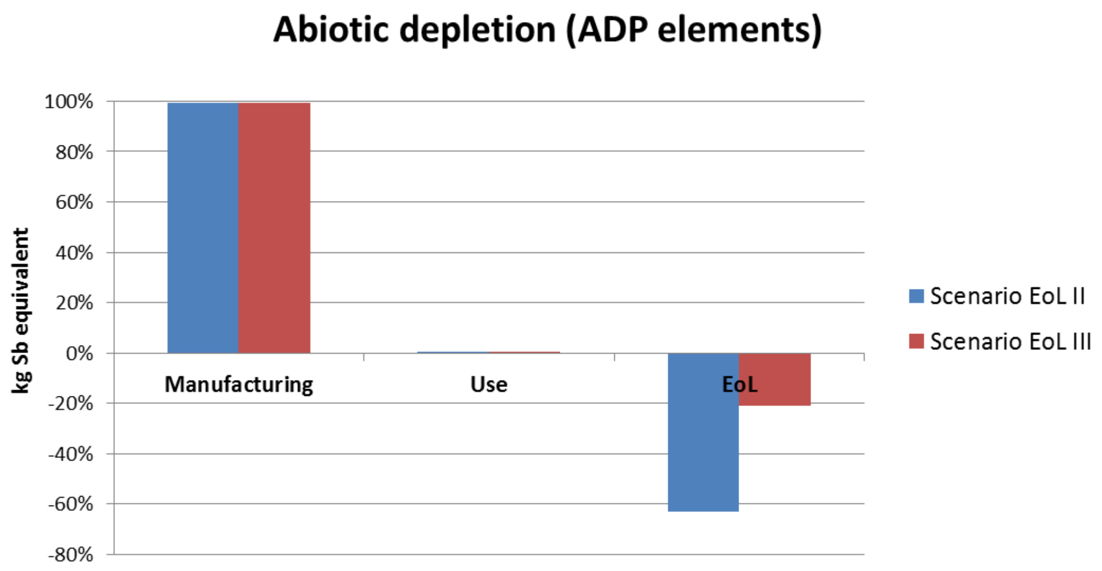


Figure 16. Abiotic depletion potential (ADP elements) of an enterprise server expressed as kg equivalent of antimony [kg $_{Sb\ eq.}$].

As illustrated in Figure 16, the lifecycle phase that generates the greatest environmental impact in terms of resource depletion is the manufacturing of the server. Table 22 shows the potential environmental impact of the manufacturing phase of an enterprise server. More than half of the potential impact is generated by the main board and processor (CPU), followed by memory cards (12%), hard risk drives (10%), and expansion cards (7%). As illustrated in figure 11, some of these components are easily accessible, especially hard disk drives, which make them easier to separate. The accessibility of components is also beneficial for reuse (see section 4.5.4).

In order to identify the impact hotspots, i.e. where changes can help to considerably reduce the overall environmental impact of the server, in the next section we analyse in further detail the potential environmental impacts of the server using the Resource-Efficiency Assessment of Products (REAPro) method.

Table 22. Potential environmental impact of the manufacturing phase of an enterprise server (in %).

Impacts ILCD/PEF recommendation	Chassis	Fan	HDD	ODD	Batteries	Main board	PSU	Expansion card	Cables	CPU	Heat pipes	Memory cards	Packaging	Transport	Electricity
Ecotoxicity for aquatic fresh water, USEtox	4.71	0.58	3.15	0.55	0.09	**79.31**	2.70	0.56	3.25	1.50	0.64	1.38	1.53	0.04	0.04
Freshwater eutrophication, EUTREND model	4.65	0.53	4.54	0.14	0.10	**78.62**	1.74	0.76	3.11	0.49	0.06	1.11	4.13	0.02	0.00
Human toxicity cancer effects, USEtox	16.95	2.06	7.65	0.78	0.04	**24.54**	3.83	4.47	0.93	**22.43**	0.30	14.94	0.85	0.21	0.21
Human toxicity non-canc. effects, USEtox	7.58	1.40	8.23	0.65	0.10	**38.02**	5.04	5.09	1.60	**17.91**	0.90	12.78	0.46	0.16	0.15
IPCC global warming, excl. biogenic carbon	**10.90**	1.33	**9.40**	0.99	0.12	**24.27**	3.75	5.93	0.15	**24.97**	0.26	**16.10**	0.53	0.96	0.70
IPCC global warming, incl. biogenic carbon	10.90	1.33	9.40	0.99	0.12	**24.57**	3.82	5.96	0.15	**24.89**	0.26	**16.12**	0.19	0.95	0.70
Marine eutrophication, EUTREND model, ReCiPe	4.43	2.43	8.50	0.87	0.47	**33.83**	5.10	6.99	1.26	**15.69**	0.16	**15.41**	4.48	0.09	0.06
Ozone depletion, WMO model, ReCiPe	**70.64**	2.61	9.11	0.71	0.01	**2.23**	8.34	0.15	0.38	0.78	0.80	0.53	3.62	0.07	0.00
Particulate matter/Respiratory inorganics, RiskPoll	5.77	1.14	10.02	0.91	0.06	**29.65**	4.46	6.41	0.20	**23.49**	0.52	**14.90**	0.52	1.78	1.69
Photochemical ozone formation, LOTOS-EUROS model,ReCiPe	8.41	1.16	9.62	1.03	0.08	**26.44**	3.86	5.98	0.14	**21.17**	0.18	**15.74**	0.54	5.45	4.86
Terrestrial eutrophication, accumulated exceedance	7.49	1.16	9.66	1.03	0.11	**27.17**	3.88	6.09	0.14	**20.67**	0.17	**15.94**	0.50	5.80	5.16
Total freshwater consumption, including rainwater, Swiss Ecoscarcity	4.92	1.15	10.58	0.86	0.21	**32.39**	4.32	5.78	0.36	**21.96**	0.54	**13.43**	2.89	0.01	0.01
CML 2001 - April 2013															
Abiotic Depletion (ADP elements)	4.42	1.22	10.31	2.12	0.00	27.71	4.02	7.40	0.66	26.36	3.48	12.29	0.01	0.00	0.00
Acidification Potential (AP)	7.12	1.06	10.15	1.07	0.07	**25.70**	3.19	6.05	0.17	**25.26**	0.20	**15.86**	0.34	3.48	3.30
Primary energy															
Primary energy demand (gross cal. value)	4.42	1.36	9.82	1.02	0.12	**25.10**	3.23	6.08	0.30	**26.14**	0.22	**18.24**	2.47	0.93	0.54

4.6. Application of the Resource-Efficiency Assessment of Products (REAPro) method

The JRC-IES has developed the Resource Efficiency Assessment of Products (REAPro) method to support environmental product policies and improve the resource efficiency of products (Ardente and Mathieux 2014). REAPro considers reusability, recyclability and recoverability (RRR) rates; recycled content; use and management of relevant materials and hazardous substances; and durability. Compared to previous analyses, REAPro facilitates a more exhaustive investigation of the relevance of reusability in terms of mass and environmental impacts.

4.6.1. Environmental analysis of reused components in enterprise servers

The 'reusability' of a product can be defined as the possibility of reusing product parts that can be diverted from the end of-life stream (ISO 22628, 2002). Some product components can be reused for remanufacturing[16] new products or as spare parts for existing products. Based on communications with enterprise server manufacturers, brokers and spare parts providers (see sections 3.2.), we identified a list of the most frequently used components of enterprise servers, including the estimated reuse rate (i.e. the percentage of components in recycled servers that are reused) (Table 23) (re-tek 2015).

The first step in the environmental assessment of reuse is the calculation of the Reusability index in terms of mass (i.e. the mass of potentially reusable parts) (Ardente and Mathieux 2012). Table 24 shows the reusability index calculated for enterprise servers. Even though chassis and power supply are greater in terms of mass, the components that are most frequently reused are those that are more valuable from a technological perspective, such as HDDs and memory cards.

Table 23. Reusable parts of enterprise server (in grams and %) (adapted from Re-Tek, 2015).

Component	Mass (g)	Reuse rate (%)	Component	Mass (g)	Reuse rate (%)
HDD	1 750	47.7	Raid card	5.2	2.1
Memory cards	135	40.1	Chassis (frames)	13 454	1.4
Processors (CPU)	54	5.2	Expansion card/Graphic cards	349	0.7
Mainboard	1 662	2.7	Power supply	3 426	5.0
Total mass of the server: 27 799 g					

[16] Remanufacturing is here defined as the process by which value is added to component parts at the end of-life in order to return them to their original as-new condition or better (definition modified from [ISO 16714, 2008]).

Table 24. Reusability index (in mass) for each reusable component.

Component	Reusability index (in mass)
	[%]
HDD	6.3
Memory cards	0.5
Processors (CPU)	0.2
Mainboard	6.0
Raid card	0.02
Chassis	48.4
Expansion card/Graphic cards	1.3
Power supply	12.3

The potential environmental benefits related to reusable parts (the reusability benefit index) has been calculated as follows[17]:

$$R'_{use,j} = \frac{\sum_i (k_i \cdot I_{i,j} - PRE_{i,j})}{P_j + M_j + O_j} \cdot 100$$

Where:

- $R'_{use,j}$ = Reusability Benefit rate for the j^{th} impact category [%]
- $I_{i,j}$ = Environmental impact of the i^{th} reusable component for the impact category ‘j’
- $PRE_{i,j}$ = Environmental impact due to the preparation for reuse of component ‘i’ for the impact category ‘j’
- P_j = Environmental impact of the production of components in the product for the impact category ‘j’;
- M_j = Environmental impact of the manufacturing of the product for the impact category ‘j’;
- O_j = Environmental impact of the operation of the product for the impact category ‘j’;
- k_i = downcycling factor for reusable component “i” [adimensional].

The lifecycle impacts of the server and the impacts of reusable components are presented in Table 25.

Concerning the downcycling factor “k”, the following assumptions are introduced:

- Memory cards and HDDs are the components mostly often reused in remanufactured products because they are less affected by technological obsolescence. For these components, a factor: k = *0.9* is assumed.

[17] Modified from (Ardente and Mathieux, 2012),

- Other parts (mainly processors and main boards) have a higher risk of obsolescence and are mainly used as spare parts for the maintenance of servers or installed in refurbished products with lower levels of performance. For these, a factor: k = *0.4* is assumed.

Concerning the impacts of preparation for reuse (*PRE*), it is assumed that the environmental impacts of manual disassembly are negligible for all reusable components. Analogously, the impacts of cosmetics are negligible (because reusable parts are all internal components). Low impacts are due to the energy used for the checking and testing of components, and some minor repairs / substitutions (when necessary) [18]. It is assumed that the environmental impacts of transport to the reuse facilities are analogous to those of transport to the manufacturing site. It is assumed that *PRE* amounts to 0.5% of the impacts of the production of the component.

Table 26 lists the calculated values of the Reusability Benefit rate. As the majority of the benefits are related to four components (HDD, memory cards, CPU and main board). The Reusability benefit index has been calculated relative to these components only (Table 27). It is observed that:

- some components (e.g. memory cards and CPU), although they are not relevant in mass, are relevant in terms of environmental impacts and potential benefits when reused;

- the potential benefits of reusable parts are generally relevant for impact categories such as: ecotoxicity and human toxicity, ionising radiation, marine eutrophication, ozone depletion and resource depletion;

- for some impact categories, the benefits amount to more than 30% of the lifecycle impacts of the server (with regard to ecotoxicity, freshwater eutrophication, human toxicity and abiotic depletion-mineral);

- benefits are relevant (between 7%-12%) even for impact categories that are largely influenced by the operation (such as GWP, acidification and primary energy demand);

- benefits are also relevant when a high-downcycling factor is assumed (for example, for the main board).

[18] According to manufacturers and spare parts providers interviewed, components are discarded when major repairs are necessary.

Table 25. Impacts of reusable components and the server on the environment

Component	Environmental impact														
	Acidific.	Ecotox. fresh water	Fresh water eutroph	Human tox. canc.	Human tox. non-canc.	GWP	GWP (incl. biogenic)	Marine eutroph	Ozone depletion	Particulate matter	Photoch. Ozone	Res. Depl. (mineral)	Terrestrial eutroph.	Fresh Water cons.	Prim. energy demand (fossil)
	[kg $SO_{2\text{-}eq.}$]	[CTUe]	[kg Peq]	[CTUh]	[CTUh]	[kg $CO_{2\text{-}eq}$]	[kg $CO_{2\text{-}eq}$]	[kg $N_{\text{-}eq}$]	[kg CFC-11_{eq}]	[kg PM2,$5_{\text{-}eq}$]	[kg NMVOC]	[kg $Sb_{\text{-}eq}$]	[Mole N_{eq}]	[UBP]	[MJ]
HDD	6.0E-01	3.2E+01	1.2E-03	1.3E-06	6.9E-06	8.6E+01	8.7E+01	3.8E-03	6.4E-07	5.7E-02	3.3E-01	1.1E-02	1.2E+00	5.7E+01	1.3E+03
Memory	9.3E-01	1.4E+01	2.9E-04	2.6E-06	1.1E-05	1.5E+02	1.5E+02	6.8E-03	3.7E-08	8.5E-02	5.4E-01	1.3E-02	2.0E+00	7.2E+01	2.4E+03
Processors (CPUs)	1.5E+00	1.5E+01	1.3E-04	3.8E-06	1.5E-05	2.3E+02	2.3E+02	7.0E-03	5.5E-08	1.3E-01	7.2E-01	2.8E-02	2.6E+00	1.2E+02	3.4E+03
Main board	1.5E+00	8.0E+02	2.0E-02	4.2E-06	3.2E-05	2.2E+02	2.3E+02	1.5E-02	1.6E-07	1.7E-01	9.0E-01	2.9E-02	3.4E+00	1.7E+02	3.3E+03
Raid card	2.2E-03	7.9E-02	4.9E-06	4.1E-09	3.0E-08	3.8E-01	4.0E-01	3.3E-05	4.0E-11	2.7E-04	1.8E-03	2.3E-05	6.9E-03	2.4E-01	5.6E+00
Chassis (frames)	2.5E-01	4.4E+01	1.1E-03	2.6E-06	4.8E-06	7.3E+01	7.4E+01	6.2E-04	4.9E-06	1.4E-02	1.7E-01	1.5E-03	5.1E-01	6.2E+00	1.8E+02
Expansion card/Graphic cards	3.6E-01	5.6E+00	2.0E-04	7.6E-07	4.3E-06	5.4E+01	5.5E+01	3.1E-03	1.1E-08	3.7E-02	2.0E-01	7.8E-03	7.6E-01	3.1E+01	7.9E+02
Power supply	1.9E-01	2.7E+01	4.5E-04	6.5E-07	4.2E-06	3.4E+01	3.5E+01	2.3E-03	5.8E-07	2.5E-02	1.3E-01	4.2E-03	4.8E-01	2.3E+01	4.2E+02
Server (materials & manufacturing)	5.9E+00	1.0E+03	2.6E-02	1.7E-05	8.4E-05	9.2E+02	9.2E+02	4.4E-02	7.0E-06	5.7E-01	3.4E+00	1.1E-01	1.2E+01	5.4E+02	1.3E+04
Server (operation)	1.6E+01	9.3E+01	3.9E-03	2.7E-06	7.6E-05	3.1E+03	3.1E+03	1.4E-01	2.3E-06	1.1E+00	6.5E+00	5.5E-04	2.3E+01	3.3E+03	7.1E+04
Total Server	**2.2E+01**	**1.1E+03**	**3.0E-02**	**2.0E-05**	**1.6E-04**	**4.1E+03**	**4.0E+03**	**1.8E-01**	**9.3E-06**	**1.6E+00**	**9.9E+00**	**1.1E-01**	**3.5E+01**	**3.8E+03**	**8.4E+04**

Table 26. Reusability benefit index for different components and various impact categories.

Component	Reusability benefit index														
	Acidific.	Ecotox. fresh water	Fresh water eutroph.	Human tox. canc.	Human tox. non-canc.	GWP	GWP (incl. biogenic)	Marine eutroph.	Ozone depletion	Particulate matter	Photoc. ozone	Res. Depl. (mineral)	Terrestrial eutroph.	Fresh water cons.	Prim. energy demand (fossil)
	[kg $SO_{2\text{-eq.}}$]	[CTUe]	[kg P_{eq}]	[CTUh]	[CTUh]	[kg $CO_{2\text{-eq}}$]	[kg $CO_{2\text{-eq}}$]	[kg $N_{\text{-eq}}$]	[kg CFC-11_{eq}]	[kg PM2,5-$_{eq}$]	[kg NMVOC]	[kg Sb-$_{eq}$]	[Mole N_{eq}]	[UBP]	[MJ]
HDD	2.5%	2.6%	3.5%	5.9%	3.9%	1.9%	1.9%	1.9%	6.1%	3.1%	3.0%	9.2%	3.1%	1.3%	1.4%
Memory	3.9%	1.1%	0.9%	11.6%	6.0%	3.3%	3.3%	3.4%	0.4%	4.6%	4.8%	10.9%	5.0%	1.7%	2.5%
Processors (CPUs)	2.7%	0.5%	0.2%	7.7%	3.7%	2.2%	2.2%	1.5%	0.2%	3.2%	2.9%	10.4%	2.9%	1.2%	1.6%
Main board	2.8%	28.7%	26.9%	8.4%	7.9%	2.2%	2.2%	3.3%	0.7%	4.1%	3.6%	10.9%	3.8%	1.8%	1.5%
Raid card	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.
Chassis (frames)	0.5%	1.6%	1.4%	5.2%	1.2%	0.7%	0.7%	0.1%	20.9%	0.3%	0.7%	0.6%	0.6%	0.1%	0.1%
Expansion card/Graphic cards	0.7%	0.2%	0.3%	1.5%	1.1%	0.5%	0.5%	0.7%	0.0%	0.9%	0.8%	2.9%	0.9%	0.3%	0.4%
Power supply	0.3%	1.0%	0.6%	1.3%	1.0%	0.3%	0.3%	0.5%	2.5%	0.6%	0.5%	1.6%	0.5%	0.2%	0.2%
Reusability benefit rate	**13.3%**	**35.7%**	**33.8%**	**41.5%**	**24.7%**	**11.2%**	**11.3%**	**11.3%**	**30.8%**	**16.9%**	**16.3%**	**46.4%**	**16.7%**	**6.7%**	**7.7%**

Table 27. Reusability benefit index relative to the four main reusable components

Component	Reusability benefit index														
	Acidific.	Ecotox. fresh water	Fresh water eutroph.	Human tox. canc.	Human tox. non-canc.	GWP	GWP (incl. biogenic)	Marine eutroph	Ozone depletion	Part. matter	Photoch. Ozone	Res. Depl. (mineral)	Terrest. eutroph	Fresh water cons.	Prim. energy demand (fossil)
	[kg $SO_{2\text{-eq}}$]	[CTUe]	[kg P eq]	[CTUh]	[CTUh]	[kg $CO_{2\text{-eq}}$]	[kg $CO_{2\text{-eq}}$]	[kg N-eq]	[kg CFC-11eq]	[kg PM2,5-$_{eq}$]	[kg NMVOC]	[kg Sb-$_{eq}$]	[Mole N_{eq}]	[UBP]	[MJ]
HDD	2.5%	2.6%	3.5%	5.9%	3.9%	1.9%	1.9%	1.9%	6.1%	3.1%	3.0%	9.2%	3.1%	1.3%	1.4%
Memory	3.9%	1.1%	0.9%	11.6%	6.0%	3.3%	3.3%	3.4%	0.4%	4.6%	4.8%	10.9%	5.0%	1.7%	2.5%
Processors (CPUs)	2.7%	0.5%	0.2%	7.7%	3.7%	2.2%	2.2%	1.5%	0.2%	3.2%	2.9%	10.4%	2.9%	1.2%	1.6%
Main board	2.8%	28.7%	26.9%	8.4%	7.9%	2.2%	2.2%	3.3%	0.7%	4.1%	3.6%	10.9%	3.8%	1.8%	1.5%
Reusability benefit rate	11.8%	32.9%	31.5%	33.5%	21.5%	9.6%	9.7%	10.0%	7.4%	15.1%	14.2%	41.4%	14.8%	6.1%	7.1%

4.6.1.1.Sensitivity analysis of reusability

A sensitivity analysis of the Reusability benefit rate has been carried out with particular regard to the values of the downcycling factor and the impacts of “preparation for reuse”. In particular, it has been assumed that:

- downcycling factors of memory cards and HDDs vary from 0.7 to 0.95
- downcycling factors of processors and main board vary from 0.2 to 0.6
- environmental impacts of the preparation for reuse vary from 0.5% to 3%

The results given in Table 28 show that values change significantly, especially for impact categories that are mostly influenced by the manufacturing and production of materials. Particularly relevant are assumptions related to the downcycling factor of main boards. Changes of impacts resulting from preparation for reuse do not greatly affect the results.

Table 28. Reusability benefit index: sensitivity analysis

Reusability benefit rate	Maximum values	Minimum values	Reusability benefit rate	Maximum values	Minimum values
Acidification	15%	6%	Ozone depletion	8%	6%
Ecotox. fresh water	48%	2%	Particulate matter	19%	7%
Freshwater eutroph.	45%	2%	Photoch. Ozone	18%	7%
Human tox. canc.	43%	16%	Res. Depl. (mineral)	53%	18%
Human tox. non-canc.	28%	9%	Terrestrial eutroph.	19%	7%
GWP	12%	5%	Freshwater cons.	8%	3%
GWP (incl. biogenic)	12%	5%	Prim. energy demand (fossil)	9%	4%
Marine eutrophication	13%	5%			

4.6.1.2. Benefits related to reused components into remanufactured product

The results presented above show that the reuse of components in remanufactured servers can lead to significant environmental benefits in terms of avoided production of brand new components. A server made up of reused components could have lower energy efficiency compared to a new server, while still having overall environmental benefits. In particular, the energy consumed during operation of a server with reused components (e_B) could be expressed as a function of the energy consumption (e_A) of a server made up of completely new components:

$$\left(e_B < \delta_j \cdot e_A\right)$$

With:

$$\delta_j = 1 + \frac{\left(\sum_i I_{i,j} - PRE_{i,j}\right)}{U_{A,j}}$$

- δ_j = ratio between the impacts (for impact category "j") of the operation of the server including reused components, compared to the impacts of the operation of a new server;
- $\sum_i I_{i,j} = \Delta P_j$ = Overall environmental impact on category "j" of components that are reused;
- PRE_j = Impact on the category "j" due to the preparation for reuse.

The values calculated for "δ_j" are given in Table 29. These calculations consider that only two types of components are reused (i.e. HDDs and memory cards) (Table 30).

It is noticed that values of "δ_j" are very different for different impact categories. For example, in the case of the reuse of four types of components (Table 29), "δ_{GWP} =1.22", which means that a server with reused components (HDDs, memory cards, CPUs and main boards) could have 22% higher energy consumption (compared to a brand new server), while still having the same GWP impact of a brand new server. When HDDs and memory cards are reused (Table 30), the server could have up to 7% higher energy consumption still having the same GWP impact of a brand new server.

Values of δ are very high for impact categories that are not greatly influenced by the operation phase (such as, for example, Resource depletion – mineral, freshwater eutrophication and human toxicity). In those cases, it can be assumed that the reuse of components is always beneficial whatever the energy consumption of the product.

Table 29. Values of factor "δ" for reuse of HDDs, memory cards, CPUs and main boards

	ΔP	PRE	U	δ
Acidific.	4.5E+00	2.3E-02	1.6E+01	1.3
Ecotox. fresh water	856.30	4.3	93.4	10.1
Freshwater eutroph.	2.2E-02	1.1E-04	3.9E-03	6.5
Human tox. canc.	1.2E-05	5.9E-08	2.7E-06	5.4
Human tox. non-canc.	6.4E-05	3.2E-07	7.6E-05	1.8
GWP	686.39	3.43	3133.69	1.22
GWP (incl. biogenic)	690.99	3.45	3124.31	1.22
Marine eutroph.	3.3E-02	1.6E-04	1.4E-01	1.2
Ozone depletion	8.9E-07	4.4E-09	2.3E-06	1.4
Particulate matter	0.45	0.00	1.07	1.41
Photoch. Ozone	2.48	0.01	6.51	1.38
Res. Depl. (mineral)	0.08	4.03E-04	5.48E-04	147.33
Terrestrial eutroph.	9.16	0.05	22.85	1.40
Freshwater cons.	421.50	2.11	3279.42	1.13
Prim. energy demand (fossil)	10319.35	51.60	70621.54	1.15

Table 30. Values of factor "δ" for reuse of HDDs and memory cards

	ΔP	PRE	U	δ
Acidific.	1.5E+00	7.6E-03	1.6E+01	1.10
Ecotox. fresh water	45.44	0.23	93.38	1.48
Freshwater eutroph.	1.46E-03	7.31E-06	3.93E-03	1.37
Human tox. canc.	3.86E-06	1.93E-08	2.69E-06	2.43
Human tox. non-canc.	1.76E-05	8.80E-08	7.58E-05	1.23
GWP	234.37	1.17	3133.69	1.07
GWP (incl. biogenic)	235.27	1.18	3124.31	1.07
Marine eutroph.	1.06E-02	5.30E-05	1.37E-01	1.08
Ozone depletion	6.75E-07	3.38E-09	2.33E-06	1.29
Particulate matter	1.42E-01	7.12E-04	1.07	1.13
Photoch. Ozone	8.64E-01	4.32E-03	6.51	1.13
Res. Depl. (mineral)	2.38E-02	1.19E-04	5.48E-04	44.14
Terrestrial eutroph.	3.20	0.02	22.85	1.14
Freshwater cons.	129.23	0.65	3279.42	1.04
Prim. energy demand (fossil)	3654.35	18.27	70621.54	1.05

4.6.2. Environmental analysis of the recyclability of servers

The recyclability rate aims to quantify the amount of materials in a product that could be recycled at its end-of-life (EoL). The calculation of the Recyclability rate index - R^*_{cyc} - (in mass) is based on the identification of different typologies of the product's parts, according to the particular EoL scenario (Ardente and Mathieux 2012). Recyclable parts are identified according to the current representative EoL treatments for the product. IEC/TR 62635 provides some data for the recycling rates of parts generally included in electrical and electronic equipment (The International Electrotechnical Commission 2012). For the calculations of recyclability, it is important to highlight that the recycling rates vary depending on the processes that parts undergo. IEC/TR 62635 classifies parts as (The International Electrotechnical Commission 2012):

Parts for selective treatment: Some parts need special treatment due to their content of hazardous substances. Generally, these parts must undergo specific extraction and separate treatment processes in accordance with current legislation (European Commission 2012). From servers, the parts to be separated are external cables/wiring, PCBs (greater than 10 cm^2), and capacitors (greater than 2.5 cm). External cables are easily removed. PCBs can be removed in advance, by specific dismantling or by other strategies (hand-picking or mechanical sorting) after preliminary shredding and fine shredding. Capacitors, which are included in PCBs, are generally manually separated after the removal of the PCBs.

Parts made of a single recyclable material (referred to as being eligible for selective recycling): Parts made of a single recyclable material that can be addressed to specific EoL channels are treated using EoL processes without further processing. This group includes parts that contain valuable materials and are easy to dismantle, such as PCBs that are smaller than 10 cm^2 and are relatively easy to separate, and parts rich in copper content (i.e. heat pipes of CPUs). The separation of these parts before shredding allows for the recovery of greater amounts of valuable materials.

Parts difficult to process: Some parts are more difficult to recycle due to their content of certain substances and/or physical design (i.e. too large for the shredder or incompatible with the material sorting process of a particular facility).

Parts that do not fall into any of the groups mentioned above undergo material separation processes together with parts from other products. Table 31 summarises the components of the server that are recycled in different ways depending on the EoL scenario.

Table 31. Classification of different parts contained in the server for recycling.

Components	Scenario EoL 2 (Selective recycling + treatment + shredding)	Scenario EoL 3 (Shredding)
Chassis	Other parts for material separation	Other parts for material separation
Fans	Selective recycling	
Hard disk drive (HDD)		
Optical disk drive (ODD)		
Batteries	Selective treatment	
Mainboard		
Power supply unit (PSU)	Selective recycling	
Expansion cards	Selective treatment	
Cables		
Processor (CPU)	Selective recycling	
Heat pipe for CPU		
Memory cards	Selective treatment	
Packaging	Selective recycling	

The recyclability rate in mass of REAPro is calculated as following:

$$RRR = \frac{\sum_{i=1}^{P} m_i \cdot X_{RRR,i}}{m} \cdot 100$$

Where:

- RRR = Reusability / Recyclability / Recoverability rates [%]
- m_i = mass of the i^{th} part of the product [kg]
- $X_{RRR,i}$ = Rates of the i^{th} part of the product that is potentially reusable/recyclable/recoverable [%]
- P = number of parts of the product [dimensionless]
- m = total product's mass [kg]

Table 32 lists the amounts of materials contained in the server, and the amount recycled under EoL scenarios 2 and 3. As observed, the amount recycled from both scenarios varies by about 600 g, with the greatest difference being for copper (264 g) followed by the amount recovered from PCBs (152 g). The recycling amounts displayed in table 32 are used to calculate the recyclability rate of servers under EoL scenarios 2 and 3. The recyclability rate of an enterprise server under EoL scenario 2 is 61.7% (see table A5 of the annex), whereas under scenario 3 (see table A6 of the annex) it is 59.6%. Although the overall difference is not significant (only 2%) the results show significant losses of valuable metals contained in small amounts. This is the case for the gold, palladium, and silver contained in PCBs, for which the recyclability rate decreases from 98-99% to 26-11% (Chancerel, Meskers et al. 2009). Such large losses are not captured by the recyclability rate in mass, which gives greater importance to materials contained in higher amounts. It is therefore useful to estimate the potential benefit of recyclability using the LCA results, as a way of identifying products' hot-spots and material losses, and potential strategies to improve their resource efficiency.

Table 33 provides more detailed figures about the amounts of materials contained in PCBs of a sample server, and the amounts recycled under scenarios 2 and 3. In terms of mass, the major difference is the amount of copper recovered by each of the EoL scenarios. In economic terms, significant amounts of high valuable metals are lost in EoL 3. A server treated according to EoL scenario 3 loses about 75% of its gold and palladium content, and almost 90% of its silver content.

Table 32. Description of the materials and their quantities in servers, and the recycled amounts under EoL scenarios 2 and 3.

Component/Materials	Mass (g)	Amount in server (g)	Recycling EoL 2 (g)	Recycling EoL 3 (g)	Losses (EoL 2 vs 3) (g)
Aluminum	- Chassis (249) - ODD (1) - 4HDD (787) - 2PSU (226)	1 263	1 185.10	1 149.07	36.03
Brass	- Cables (7)	7	6.65	4.9	1.75
Copper	- Chassis (179) - ODD (7) - Cables (81) - Heat pipe (442) - 4Fan (78) - 4HDD (7) - 2PSU (13)	806.56	747.98	483.72	264
Steel	- Chassis (12,265) - ODD (115) - Heat pipes (140) - 4Fan (386) - 4HDD (547) - PSU (1408)	14 861	13 996.18	13 970.21	25.97
Ferrous metals	- 4 Fan (55) - 4HDD (152) - 2PSU (9)	216	151.11	151.11	0
Zinc	cables (96)	96	67.20	57.6	10
ABS	- Chassis (348) - ODD (12)	360	266	266.40	0
EVA	- 2PSU (75)	75	0	0	0
HDPE	- ODD (28) - Cables (104) - Packaging (78)	210	97.76	0	98
PBT	- 4 Fan (206) - 2PSU (34)	240	0	0	0
PC	- Chassis (282) - ODD (7)	289	0	0	0
PCABS	- 4Fan (220) - 4HDD (68) -2PSU (36)	324.28	0	0	0
PCFR40	- 2PSU (51)	51	0	0	0
PCGF	- 4HDD (52)	52	0	0	0
PUR	- Cables (2)	2	0	0	0
PVC	- Cables (145)	145	0	0	0
Styrofoam	- Packaging (1026)	1 026	0	0	0
Synthetic rubber	- Cables (35)	35	0	0	0
Other materials					
Cables	- PSU (31)	31	7.40	7.40	0
Electronics	PCBs (including capacitors): - Mainboard (1667) - Expansion card (349) - CPU (54) - Memory (135) - 4HDD (68) - 2PSU (1543) - Chassis (131) - ODD (19)	3 966	596.12	444.32	151.80
Paper	- Packaging (3629)	3 629	0	0	0
Others (solder)	- ODD (2)	2	0	0	0
Neodymium magnets	- 4HDD (68)	68	0	0	0
Batteries	- Coin cell CR2032 (1.6) - Li ion prismatic (43)	44.6	20	20	0
Total		**27 799**	**17 142**	**16 555**	**587**

ABS: acrylonitrile-butylene-styrene; EVA: ethylene vinyl acetate HDPE: high density polyethylene; PBT: polybutylene terephthalate; PC: polycarbonate; PCABS: polycarbonate acrylonitrile-butylene-styrene; PCFR40: polycarbonate with flame retardant; PCGF: polycarbonate glass fibre; PUR: polyurethane; PVC: polyvinyl acetate

Table 33. Description of the materials and their amounts in printed circuit boards contained in a sample server (all amounts are in grams).

	Amount in server	EoL 2	EoL 3	Losses (EoL 2 vs EoL 3)
Printed circuit boards (Total mass)	3 966	596.12	444.32	151.80
Brominated Epoxy Resins	1 176.97	0.00	0.00	0
Glass Fibre	1 722.01	0.00	0.00	0
Aluminum	333.78	15.58	16.689	-1.1126
Copper	705.295	573.08	423.177	149.90
Gold	0.9620	0.91	0.250	0.6574
Iron	3.5600	0.47	0.178	0.2925
Nickel	0.7779	0.58	0.194	0.3874
Palladium	0.3971	0.32	0.103	0.2210
Silicon	6.5600	0.00	0.000	0
Silver	0.4830	0.40	0.053	0.3467
Tin	9.4130	4.78	3.671	1.1050
Titanium	3.6200	0.00	0.000	0
Magnesium	0.0039	0.00	0.000	0
Neodymium	0.2100	0.00	0.000	0
Lead	0.0032	0.00	0.002	-0.0019
Other materials	1.9101	0.00	0.000	0

4.6.2.1. Environmental benefits of the recyclability of servers

Within the project "Integration of resource efficiency and waste management criteria in European product policies – Second phase", a series of environmental indicators, including the Recyclability Benefit Rate (RBR), were developed as part of the REAPro method. The RBR accounts for potential benefits by comparing the benefits of the potential recycling of materials compared to the lifecycle impacts of a baseline scenario (when the product is not recycled, but landfilled). Based on the formulas developed by Ardente and Mathieux (2012), the RBR index has been modified as follows:

$$RBR_i^* = \frac{\sum_n k_n \cdot P'_n - R_1 - \sum_n R_{2,n}}{P+M+O} \cdot 100$$

- RBR* = revised Recyclability Benefit Rate [%]
- k_i = downcycling factor for recycled material "n" [adimensional]
- P'_n = Environmental impact due to production of material "n" [impacts]
- R_1 = Environmental impact due to the treatment of the server in the recycling plant [impacts]
- $R_{2,n}$ = Environmental impact due to the recycling of material "n" and the production of secondary materials [impacts]
- P_j = Environmental impact of the production of components in the product for the impact category 'j'
- M_j = Environmental impact of the manufacturing of the product for the impact category 'j'
- O_j = Environmental impact of the operation of the product for the impact category 'j'

The formula distinguishes between the impacts "R_2" of processing the waste and the impacts "R_1" due to the production of secondary raw materials from recycled materials. The term "R_1" includes:

- impact due to the transport of the waste[19]

- impact of pre-processing[20]

- impact of shredding [21]

- impact of sorting [22]

[19] This accounts for all transport from the final user to the recycling facility.
[20] This could include, for example, the use of electricity to run machine tools used for manual disassembly.
[21] This could include, for example, the use of electricity and auxiliary materials needed to run the shredders, and the emission of dust from the machines.
[22] This could include, for example, the electricity used by magnetic separators and waste water produced by the plants for the density separation of plastics.

The term “$R_{1,n}$” includes all the impacts due to the processing of the materials, which have been sorted in the waste treatment plant. These impacts are dependent on the type of material “n”, such as: the transport of the scrap from the waste-recycling facility to the treatment plant; the impacts of processing scrap materials (e.g. further fine shredding); the impacts of further treatment of scrap materials (such as sorting, melting, refinement, extrusion) up to the production of the secondary material.

The RBR of all the impact categories considered are given in tables 34, 35, and 36. For EoL scenario 2 (table 34), environmental benefits of over 60% are achieved for the impact categories of ecotoxicity for aquatic freshwater, freshwater eutrophication, and abiotic depletion of elements. Over 35% of the benefits are for ozone depletion potential. For human toxicity, acidification and particulate matter, the potential savings are about 15%, 10% and 8%, respectively. For the other impact categories, benefits vary from 1 to 5%.

The potential environmental benefits of EoL scenario 3 (table 35) are more modest than those of EoL scenario 2. The impact categories with the greatest potential savings are ozone depletion, abiotic depletion of elements, ecotoxicity of aquatic freshwater, and freshwater eutrophication. For the other impact categories, benefits vary from 1 to 9%. Table 35 compares the potential benefits of both scenarios. This comparison shows that for the ecotoxicity of aquatic freshwater, freshwater eutrophication and abiotic depletion of elements, EoL scenario 2 provides over 40% more benefits than EoL scenario 3. For the remaining impact categories, the benefits of EoL scenario 2 are not greater than 10%.

As illustrated in table 33, of all CRM contained in PCBs only palladium is currently recovered, with recyclability rates of 80% and 25% for EoL scenarios 2 and 3 respectively. All in all, the extraction of components containing CRM such as magnets in HDDs, batteries, connectors, and some PCBs can significantly help advance the recycling of CRM as new recycling technologies become available.

Table 34. Recyclability benefit rate for enterprise servers under EoL scenario 2

Impact category	Indicator	Unit	Production (P) and Manufacturing (M)	Operation (O)	Recycling (R) EoL scenario 2	Recyclability Benefit Rate (EoL scenario 2)
Ecotoxicity for aquatic freshwater	USEtox (recommended)	[CTUe]	1003.46	93.38	732.10	**67%**
Freshwater eutrophication	EUTREND model, ReCiPe	[kg P eq]	2.58E-02	3.93E-03	1.94E-02	**65%**
Human toxicity cancer effects	USEtox (recommended)	[CTUh]	1.71E-05	2.69E-06	2.98E-06	**15%**
Human toxicity non-canc. effects	USEtox (recommended)	[CTUh]	8.38E-05	7.58E-05	2.28E-05	**14%**
Climate change	IPCC global warming, excl. biogenic carbon	[kg CO_2-Eq.]	918.80	3133.69	58.82	**1%**
Climate change	IPCC global warming, incl. biogenic carbon	[kg CO_2-Eq.]	922.16	3124.31	54.14	**1%**
Marine eutrophication	EUTREND model, ReCiPe	[kg N-Eq.]	4.44E-02	1.37E-01	4.78E-03	**3%**
Ozone depletion	WMO model ReCiPe	[kg CFC-11 Eq.]	7.00E-06	2.33E-06	3.48E-06	**37%**
Particulate matter/Respiratory inorganics	RiskPoll	[kg PM2,5-Eq.]	5.71E-01	1.07E+00	1.31E-01	**8%**
Photochemical ozone formation	LOTOS-EUROS model, ReCiPe	[kg NMVOC]	3.41	6.51	0.47	**5%**
Terrestrial eutrophication, accumulated exceedance		[Mole of N Eq.]	12.49	22.85	1.53	**4%**
Total freshwater consumption, including rainwater	Swiss Ecoscarcity	[UBP]	538.23	3279.42	31.60	**1%**
Abiotic Depletion (ADP elements)	CML2001 - Apr. 2013	[kg Sb-Eq.]	1.05E-01	5.48E-04	6.67E-02	**63%**
Abiotic Depletion (ADP fossil)	CML2001 - Apr. 2013	[MJ]	10 130.39	34 838.60	450.92	**1%**
Acidification Potential (AP)	CML2001 - Apr. 2013	[kg SO_2-Eq.]	5.88	15.73	2.14	**10%**
Primary energy demand	ren. and non ren. resources (gross cal. value)	[MJ]	13 020.03	70 621.54	695.92	**1%**

Table 35. Recyclability benefit rate for enterprise servers under EoL scenario 3

Impact category	Indicator	Unit	Production (P) and Manufacturing (M)	Operation (O)	Recycling (R) EoL 3	Recyclability Benefit Rate (scenario EoL 3)
Ecotoxicity for aquatic freshwater	USEtox (recommended)	[CTUe]	1003.46	93.38	222.51	**20%**
Freshwater eutrophication	EUTREND model, ReCiPe	[kg P eq]	2.58E-02	3.93E-03	5.44E-03	**18%**
Human toxicity cancer effects	USEtox (recommended)	[CTUh]	1.71E-05	2.69E-06	1.79E-06	**9%**
Human toxicity non-canc. effects	USEtox (recommended)	[CTUh]	8.38E-05	7.58E-05	8.46E-06	**5%**
Climate change	IPCC global warming, excl. biogenic carbon	[kg CO2-Equiv.]	918.80	3133.69	49.15	**1%**
Climate change	IPCC global warming, incl. biogenic carbon	[kg CO2-Equiv.]	922.16	3124.31	44.52	**1%**
Marine eutrophication	EUTREND model, ReCiPe	[kg N-Equiv.]	4.44E-02	1.37E-01	1.54E-03	**1%**
Ozone depletion	WMO model ReCiPe	[kg CFC-11 eq]	7.00E-06	2.33E-06	3.11E-06	**33%**
Particulate matter/Respiratory inorganics	RiskPoll	[kg PM2,5-Equiv.]	5.71E-01	1.07E+00	6.16E-02	**4%**
Photochemical ozone formation	LOTOS-EUROS model, ReCiPe	[kg NMVOC]	3.41E+00	6.51E+00	2.56E-01	**3%**
Terrestrial eutrophication, accumulated exceedance		[Mole of N eq.]	12.49	22.85	0.82	**2%**
Total freshwater consumption, including rainwater	Swiss Ecoscarcity	[UBP]	538.23	3279.42	17.21	**0%**
Abiotic Depletion (ADP elements)	CML2001 - Apr. 2013	[kg Sb-Equiv.]	1.05E-01	5.48E-04	2.24E-02	**21%**
Abiotic Depletion (ADP fossil)	CML2001 - Apr. 2013	[MJ]	10 130.39	34 838.60	346.73	**1%**
Acidification Potential (AP)	CML2001 - Apr. 2013	[kg SO2-Equiv.]	5.88	15.73	0.87	**4%**
Primary energy demand	ren. and non ren. resources (gross cal. value)	[MJ]	13 020.03	70 621.54	490.30	**1%**

Table 36. Recyclability benefit rate for enterprise servers under EoL scenarios 2 and 3

		Recyclability Benefit Rate (scenario EoL 2)	Recyclability Benefit Rate (scenario EoL 3)	Difference between RBR of EoL 2 and EoL 3
Ecotoxicity for aquatic freshwater	USEtox (recommended)	67%	20%	**46%**
Freshwater eutrophication	EUTREND model, ReCiPe	65%	18%	**47%**
Human toxicity cancer effects	USEtox (recommended)	15%	9%	**6%**
Human toxicity non-canc. effects	USEtox (recommended)	14%	5%	**9%**
Climate change	IPCC global warming, excl. biogenic carbon	1%	1%	**0%**
Climate change	IPCC global warming, incl. biogenic carbon	1%	1%	**0%**
Marine eutrophication	EUTREND model, ReCiPe	3%	1%	**2%**
Ozone depletion	WMO model ReCiPe	37%	33%	**4%**
Particulate matter/Respiratory inorganics	RiskPoll	8%	4%	**4%**
Photochemical ozone formation	LOTOS-EUROS model, ReCiPe	5%	3%	**2%**
Terrestrial eutrophication, accumulated exceedance		4%	2%	**2%**
Total freshwater consumption, including rainwater	Swiss Ecoscarcity	1%	0%	**0%**
Abiotic Depletion (ADP elements)	CML2001 - Apr. 2013	63%	21%	**42%**
Abiotic Depletion (ADP fossil) [MJ]	CML2001 - Apr. 2013	1%	1%	**0%**
Acidification Potential (AP)	CML2001 - Apr. 2013	10%	4%	**6%**
Primary energy demand	ren. and non ren. resources (gross cal. value)	1%	1%	**0%**

5. Evaluation of potential resource-efficiency requirements for the Ecodesign regulation of enterprise servers

As resource efficiency is becoming a cornerstone to achieving a more circular economy in the EU, new regulations for products entering the EU market shall also adapt to include resource savings aspects. Based on the findings obtained by applying the Resource-Efficiency Assessment of products (REAPro) method to a server, this section proposes some potential resource-efficiency measures that could be included in the upcoming Ecodesign regulation for enterprise servers (Lot 9). The potential resource measures discussed in this section refer to promotion of products with reused parts, the provision of technical documentation, the design for extraction of some key components, and the provision of diagrams to facilitate the location of certain critical materials. Some of these measures are based on measures developed by the JRC IES during the past years for other energy-related product groups.

5.1. Potential requirements for reuse

The reuse[23] of products and components is key to saving resources and has high economic potential (VDI 2343, 2014; EN 62309). According to the EU Waste Framework Directive, reuse is also at the highest levels of the waste hierarchy, preferable to recycling and recovery (European Parliament, 2008).

Section 4.6 of this report applied and discussed a method for the assessment of the environmental benefits of reusing servers. Previously calculated indices could be used to establish requirements that promote the reuse of components. In particular, values of "δ_j" can be used to propose a bonus for servers that include reused components[24].

For example, when the annual total energy consumption (E_{TEC} in kWh/year)[25] is established for new products, lower thresholds could be set for products that include reused components, and are sold "as-new"[26]. An example is given in the following:

[23] '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.

[24] A similar approach has been used in EU policies for other aspects, as the content of materials with high environmental impacts. For example the implementing measure on the Ecodesign of "air conditioners and air fans" established that [EC, 2012]: "bonus is proposed under the ecodesign requirements to steer the market towards the use of refrigerants with reduced harmful impact on the environment. The bonus will lead to lower minimum energy efficiency requirements for appliances using low global warming potential (GWP) refrigerants".

[25] The "ETEC" is established through e.g. the preparatory and implementation phases of Ecodesign requirements.

[26] This means that the product is brought to its original manufacturing state in "as-new" condition, both cosmetically and functionally. For example, see standard (EN 62309, 2004).

Requirement for enterprise servers with reused parts:

(Pre-condition: established that the annual total energy consumption of a server, without reused components, shall not exceed the "E_{TEC}" values)

The annual total energy consumption of servers, reusing at least the HDD, memory card, CPU and main board, shall not exceed the value "$\delta_j \cdot E_{TEC}$" (in kWh/year)[27]. δ_j will have a value of between 7% and 20% depending on the number of components reused.

For the verification of the requirement, manufacturers should provide evidence regarding the reused components (e.g. documentation on the original products in which the components were first used and their subsequent use in the refurbished product; harmonised labelling of components and products).

The aim of this requirement is to allow for the fact that a refurbished product could have higher annual total energy consumption which still generating overall environmental benefits. It this way, this requirement will not be a burden on manufacturers that produce new products, and will represent an incentive to manufacturers that want to commercialise refurbished products. When the annual total energy consumption is not set, a bonus could be foreseen for manufacturing products with reused parts, for example, in the calculation of energy efficiency indexes, or in the assignment of energy labels.

For the verification of the requirement, manufacturers should provide evidence regarding the reused components (e.g. documentation about the original products in which the components were first used and their subsequent use in a refurbished product). In order to verify the requirements, further work will have to be carried out to develop standardised information on reused parts. The mandate to be issued by the EC to the European Standardisation Organisations in support of the implementation of Directive 2009/125/EC with regard to ecodesign requirements on material-efficiency aspects could be a good platform for the development of such information.

Some examples of documentation on reused components is discussed in the VDI 2343 standard (2014). The identification of reusable products "should be achievable using automated identification systems (auto-ID systems). With these systems, data are recorded on some appropriate medium (barcode, RFID tag), which then links the information permanently to the product. Readout units (scanners, readers) can pick up this information automatically when the product arrives, and process it electronically. This is done in the form of a standardised, unambiguous numerical code, whose digits represent the product's features such as manufacturer (brand), manufacturing date and item type. In addition to the numerical code's information content further data relevant for end-of-life management can be provided

[27] The value of "δ_j can refer to any of the values of Table 29 and 30 or an average value calculated among two or more impacts categories.

(e. g. material composition, pollutants and valuable substances that need to be treated selectively, disassembly instructions)".

The reuse of parts is strongly influenced by the ability to disassemble the product. The EN 62309 (2004) standard establishes that "to reduce the costs of recovering parts that can be used, designers should think about how the product will be disassembled at the end of its life. The more complex the design the more difficult and expensive it will be to recover the parts. If the disassembly is below a certain cost level, the quantity of products containing reused parts may increase" (EN 62309, 2004). In order to facilitate the reuse of their components, products should be designed in such a way as to facilitate the accessibility and separability of their parts, for example reducing the disassembly "depth" and the disassembly/dismantling time (Figure 17) (EN 62309, 2004).

Moreover, design for disassembly could help increase the resource efficiency of the product for other purposes, such as the recycling and energy recovery. The following sections illustrate some examples of requirements regarding design for disassembly.

Level of detail		Building structure	Connections	Materials
General	➔	Recycling concept	Non-destructive disassembly	Ability to recycle
Product specific	➔	Modularity	Connection category, diversity	Utilization compatibility
Parts specific	➔	Accessibility	Dismantling depth and dismantling time	Material diversity
Material specific	➔	Separability	Dismantling time	Material selection, material compatibility

Figure 17. Design for reuse aspects of a building structure, connections, and materials (EN 62309).

5.2. Potential requirements of design for disassembly, repair, re-use, recycling and recovery of enterprise servers

As illustrated in the previous sections, some server components generate most of the environmental impact during manufacturing, namely the main board, processor, memory cards and HDDs. These latter components are generally designed to allow for their ease of extraction without any prior treatment (as shown in figure 10). Memory cards are accessible in most cases once the top cover of the server is removed. Accessing the main board and processor requires several steps (see figure 10) which are sometimes difficult due to the use of particular fastening techniques (including gluing and welding).

Although batteries contribute marginally to the overall environmental impact of the manufacturing of the server (see table 22), some regulations call for their extraction (European Commission 2006; European Commission 2012; European Commission 2013).

Another reason for including batteries in the list of components to be extracted is their high content of critical raw materials, mainly cobalt for which recycling technology is already available in the market, as illustrated in section 4.3 of this report.

A study of the environmental benefits related to reuse and recycling show that the preventive extraction of these components leads to significant resource savings. We therefore propose some potential requirements to facilitate their disassembly.

Requirement of design for disassembly, repair, reuse, recycling and recovery of enterprise servers:

Manufacturers shall ensure that servers are designed so external enclosures shall be removable by hand or with commonly available tools. The following four types of components (when present) shall be identified, accessible and removable by hand or with commonly available tools:

- printed circuit board assemblies, including memory cards (larger than 10 cm^2);
- batteries;
- hard disk drives;
- processor.

The abovementioned components shall be:

- accessible: this shall be ensured by documenting the sequence of disassembly operations needed to access the targeted components, including for each of these operations: type of operation, type and number of fastening technique(s) to be unlocked, and tool(s) required; and
- extractable: servers shall be designed so that no fastening by welding or gluing is encountered for all the disassembly operations leading to the extraction of the above-listed components (some exemptions could be foreseen for thermal paste and adhesives used to bind heat sinks to printed circuit boards).

Data deletion of potentially reusable data storage equipment (i.e. hard disk drives, memory cards) shall be ensured by using methods described in section 3.2.1.3 of this report.

5.3. Potential requirement on technical information

The provision of technical documentation about a server can also significantly contribute to further resource savings and reuse, especially during recycling. One key aspect is the location of valuable metals in servers (such as copper, gold and silver, and also critical raw materials such as palladium and rare earth elements). As previously discussed in the report, differentiating between PCBs with high and low content of these metals can be extremely useful in order to select the most appropriate recycling processes. The present study also revealed that a significant amount of CRM is concentrated in connectors. Ongoing research and technological development are focusing on the recovery of these metals from electronic products. Identifying their locations will therefore facilitate their harvesting and recycling (see section 3.2.2).

The inclusion of an exploded diagram of the server would benefit not only refurbishments and recycling, but would also facilitate the maintenance of the server as parts would be more easily located. Documentation about the sequence of disassembly, as illustrated in figure 10, would help specialised technical services and recyclers to better prepare operators and reduce the time for the disassembly of certain components, such as processors and main boards, which generate the greatest environmental impact and also have the greatest concentrations of valuable metals for recycling.

The requirement of including an exploded diagram of products on the interior of the main cover and in server's manual is also being discussed as a potential resource-efficiency criterion for Ecodesign in other product groups as commercial refrigerators, and EU Ecolabels for computers. In the last report, a more detailed study illustrating the step-by-step process to extract certain components proved to be an accepted option for manufacturers. The inclusion of an exploded diagram to facilitate the location of some components to promote reuse and recycling of this product group is also one of the criteria included in the draft of the environmental standard for servers "NSF 426" (NSF International 2015).

It is also highlighted the need of using standardised templates for manuals and other relevant information, as for example, the use of the Open manual format (oManual) (Institute of Electrical and Electronics Engineers 2013).

Requirement for the provision of technical documentation of enterprise servers

Manufacturers, and/or importers in the European Union shall provide a 'resource-efficiency report' containing information relevant for the disassembly, reuse, recycling and/or recovery at end-of-life of enterprise servers free of charge and with no access restrictions. Information contained in the resource-efficiency report shall include the information provided by the manufacturer for use by its technicians. The report shall be made available, for each product family architecture, in a website accessible by third parties and kept available for seven years from the day on which the last model was placed on the market. The report shall include at least the following:

(i) the exploded diagram of the product showing the location of components/materials with special handling as identified by WEEE Directive 2012/19 EU annex VII, and targeted components listed in the requirement for disassembly, reuse, recycling and recovery, and including the specifications of each component;

(ii) documentation of the sequence of the disassembly operations, illustrating the step-by-step instructions as to how to access these components; each of these operations shall be described in terms of type of operation (e.g. unscrewing, removing, levering, positioning), type and number of fastening techniques to be unlocked, and tool(s) required;

The latest version of firmware to test the functionality and compatibility of different components in the server shall be also available to companies dealing with maintenance, reuse and upgrading of servers (including brokers, spare parts repairer, spare parts provider and third party maintenance).

5.4. Declaration of critical raw materials

Considering the European policy on raw materials[28], the electronic equipment industry is recognised as one of the major users of some CRM identified as critical within the European Raw Materials Initiative[29]. Although the recovery of rare earths from electronic waste is not yet fully established, this resource should not be sent to landfill, in line with the objectives of

[28] Commission Communication on "Tackling the challenges in commodity markets and on raw materials", COM(2011) 25 final, 2.2.2011. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0025:FIN:EN:PDF

[29] Commission Communication "On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative", COM(2014) 297 final, 26.5.2014, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0297&from=EN

waste policies[30]. An option that would help progress towards the recycling of rare earths and other critical raw materials would be the provision of information about the location of these metals within the product, in this case HDDs and other components in the server. An example of the material declaration of CRM is the draft regulation for electronic displays, which includes the voluntary provision of the average amount of indium contained in electronic displays. The latest draft of the NSF standard for servers included also a criterion for reporting the type and location of magnet in HDDs using a QR code on the external enclosure of the HDD (NSF International, 2015). As research about the recycling of CRM advances, the location and harvesting of components with high concentrations of CRM will become even more relevant. This is particularly the case of neodymium boron iron magnets the recycling of which is currently at the pilot scale but is expected to increase in the near future.

Requirement for critical raw material location of enterprise servers

Information about the location and quantities of CRM, especially rare earths contained in HDDs, shall be provided by manufacturers for each product family architecture. This information shall be submitted to a centralised database organised by industry to consolidate the volume of CRM in servers, which will provide reports or be accessible to recyclers or their representative organisations.

The provision of information on the location and content or CRM could be provided by manufacturers either through a voluntary approach (as e.g. proposed for indium in electronic displays[31]) or through mandatory requirements (as e.g. proposed for rare earths in fans[32]).

[30] Commission Communication "Towards a circular economy: A zero waste programme for Europe", COM(2014) 398 final, 2.7.2014, http://eur-lex.europa.eu/resource.html?uri=cellar:50edd1fd-01ec-11e4-831f-01aa75ed71a1.0001.01/DOC_1&format=PDF

[31] European Commission. Possible requirements for electronic displays. Consultation Forum on displays. December 2014. (http://www.eceee.org/ecodesign/products/televisions)

[32] European Commission. Review of Regulation 327/2011 with regard to ecodesign requirements for fans driven by motors with an electric input power between 125 W and 500 kW. Explanatory Notes. (http://www.eceee.org/ecodesign/products/ventilation_fans)

6. Conclusions

The number of studies that analyse enterprise servers from an environmental perspective is rather limited due to their complexity (diversity of components), and the lack of access to quantitative data about certain components. This report describes an extensive literature survey of relevant aspects (section 3), including information about the bill of materials (BoM) and quantitative data of servers, a description of the end-of-life (EoL) phase of servers, the results of an environmental assessment, and the material-efficiency criteria included in various environmental schemes. An effort to provide a more exhaustive description of the BoM is made in sections 4.1 to 4.4. These sections build upon the BoM included in the preparatory study being carried out on the Ecodesign of enterprise servers (Lot 9), to ensure consistency between both studies. In fact, the current report has been developed in close collaboration with the consultants developing the preparatory study, and some of results of the present study have been provided as input to the preparatory study, specifically those regarding estimates of the content of critical raw materials in servers, more advanced breakdowns of the material composition of some components, and the potential environmental impacts of the manufacturing of printed circuit boards (PCBs). This information was used to support the application of the Methodology for the Ecodesign of Energy-related Products (MEErP) and the environmental assessment carried out as part of the preparatory study.

One of the most significant sections of this report is the analysis of the material composition and potential environmental impacts of PCBs. This analysis goes beyond previous studies in the literature by including a more detailed breakdown of the materials included in semiconductors and other components of PCBs. Data for such estimates are based on a detailed analysis carried out to identify and quantify the components of PCBs extracted from sample servers, and full material declarations from world-leading semiconductor manufacturers (see table A4 of the Annex). The results obtained represent a novel approach to analysing PCBs, as previous estimates were made based on the results of chemical analyses of PCBs that are specific to some products, or even, in some cases, mixtures of PCBs collected by recyclers.

The information gathered shows that a server contains significant amounts of base metals such as steel (15 kg), aluminium (1.5 kg) and copper (1.5 kg), but also some scarce and critical metals such as cobalt (9.27g), gold (0.96 g), lithium (1.14g), neodymium (14.63g), palladium (0.40 g), silicon (11.23g) and silver (0.48g). While the recycling of base metals is generally well established, scarce and critical metals that are present in tiny amounts are only partially recycled. Some metals such as palladium are already recycled, whereas, despite great advances being made at the pilot scale, the industrial-scale recycling of others (such as neodymium and silicon) is not yet well-established.

This in-depth analysis of PCBs provides a more comprehensive and detailed environmental assessment of servers, in particular with regard to their manufacturing and EoL (reuse and recycling)[33]. A detailed study of the composition of servers shows that most of the environmental impacts of manufacturing are related to the manufacturing of the main boards and central processing units (CPUs), followed by memory cards, hard disk drives (HDDs), and expansion cards. The accessibility of these components can benefit both reuse and recycling as it facilitates their separation from the other components and helps increase the recovery yield of some materials, especially precious metals such as gold, silver and palladium (see section 4.5.4).

The report defines two new indicators to evaluate the benefits of reuse (EoL scenario 1): the reusability index (in mass) and the reusability benefit rate based on impact category results.

Both indices could be used to establish requirements that promote the reuse of components, as servers can be still environmentally convenient even when their energy efficiency is lower than that of new units. In this study, they have been calculated for the most commonly reused parts of the HDDs, memory cards, CPUs and main boards. The results show that memory cards and processors are highly relevant in terms of the potential environmental benefits of their reuse, even though they represent only a small percentage of the mass of the server. The environmental benefits of their reuse influence ecotoxicity, human toxicity, ionising radiation, marine eutrophication, ozone depletion and resource depletion of elements, in some cases accounting for over 30% of the lifecycle impacts of the server. Benefits amounting to 7-12% are also obtained for environmental impact categories that are largely influenced by the use phase, such as global warming potential (GWP), acidification and primary energy demand. The benefits are relevant even when high levels of downcycling prevail (where reuse is unfeasible due to technological obsolescence).

The analysis of potential recycling scenarios found that the combination of manual and automatic recycling treatments (as in EoL scenario 2) generates far fewer environmental impacts than recycling using unsorted shredding with other electrical and electronic equipment (as in EoL scenario 3). There are conflicting results regarding which lifecycle stage has the greatest potential environmental impact, as the impacts on some environmental categories are greater during the manufacturing phase, and on others during the use phase. Environmental impact categories, such as for instance global warming potential (GWP) and primary energy consumption, are heavily dominated by electricity consumption and are more impacted during the use phase; whereas categories that are dominated by the use of resources, such as ecotoxicity and the abiotic depletion potential of elements, are more impacted during the manufacturing phase. Most of the higher potential savings under scenario 2 are due to the greater recovery of metals in small amounts such as gold, palladium and silver, whose recycling rates vary from 26% to almost 99%.

Indicators of recyclability calculated using the REAPro[34] method showed the recyclability rates of scenarios 2 and 3 to be 61.7% and 59.6% respectively. Although the differences are

[33] Assumptions concerning the use phase have been aligned to those of the ongoing preparatory study on the Ecodesign of enterprise servers (Lot 9).
[34] Resource Efficiency Assessment of Products (REAPro) method. For further details, see Ardente and Mathieux (2014).

not great in terms of mass, they are still significant for some critical metals included in the PCBs, such as gold, palladium and silver, whose recycling amount drops from 98-99% (under scenario 2) to 11-26% (under scenario 3). In terms of the recyclability benefit rate, the environmental benefits of scenario 2 are over 60% greater than those of scenario 3 for impact categories such as the ecotoxicity of aquatic freshwater, freshwater eutrophication, and the abiotic depletion of elements. The potential savings under scenario 2 in terms of human toxicity, acidification and particulate matter are about 15%, 10% and 8% greater than those under scenario 3, respectively. For the remaining the impact categories, the benefits of both scenarios are similar (with variations of 1-5%).

Based on these results, and in line with the material-efficiency requirements for servers suggested by other environmental schemes, we proposed four resource-efficiency requirements for enterprise servers.

Requirement 1: The reuse of components in servers aims to facilitate the entry of servers with reused components into the market by introducing bonus systems (e.g. by reducing the potential threshold for total annual energy consumption). A server refurbished with reused components (HDDs, memory cards, CPUs and main boards) has similar environmental benefits (in terms of GWP) compared to those of a new server with 22% higher energy efficiency. A server that only reuses HDDs and memory cards would have the same GWP as a server with 7% higher energy efficiency. In order to test the efficacy of this requirement, systems that can trace reused components are needed. Some standards could be developed to support the traceability of reused components[35], including existing standards on design for reuse.

Requirement 2: The design for disassembly, reuse and recycling, and recovery aims to facilitate the access, separation and collection of valuable materials from some parts of the server. Some components, such as HDDs and memory cards, are generally designed to allow for ease of extraction, whereas further steps are needed for the extraction of the main boards and processors. Although the recyclability rates under scenarios 2 and 3 are very similar, there is a great difference in the recovery mass of some critical metals included in the PCBs, such as gold, palladium and silver, with a recycling rate of 98-99% under scenario 2 compared to 11-26% under scenario 3. A more in-depth analysis of the results shows that the recycling of servers using a combination of manual and automatic treatment (as in scenario 2) also generates much lower environmental impacts (e.g. in terms of ecotoxicity and human toxicity) than their recycling by unsorted shredding (as in scenario 3). The requirement is designed to improve the accessibility and extractability of these components, thus facilitating reversible disassembly for reuse and dismantling for recycling, and generally enhancing the recovery of minor metals, still highly relevant from a raw material criticality perspective.

Requirement 3: the provision of technical information will help ensure the special handling and accessibility of targeted components such as button batteries and processors. The documentation of the sequence of the disassembly operations can also help further

[35] For example, standard VDI 2343 - Part 7 “Recycling of electrical and electronic equipment - Re-use” (2014)

develop automatic systems for harvesting components. If servers are to be reused and refurbished, appropriate firmware is required to test the functionality of and compatibility between components in the server[36].

Requirement 4: the provision of information concerning critical raw materials would help shed light on the type and amount of materials included in the PCBs of a server. Information about the location and amount of critical raw materials in electrical and electronic equipment would significantly help monitor the use of relevant materials, and provide estimates of their potential availability for recycling in the future.

[36] The lack of firmware has been highlighted by reuse and refurbishing companies as one of the main barriers to the reusability of servers.

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9. Annex

Table A1. Other methods available for data sanitisation and deletion.

Sanitation method	Overwriting (number)	Description of overwriting cycles
Bruce-Schneier algorithm	7	first: zero second: one third to seventh: random character
Peter-Gutmann algorithm	35	random character
Pfitzner (created by Roy Pfitzner)	33	random character
Random data	customized	random character
Secure Erase (PATA and SATA based hard drives)	1	First: Writes a binary one or zero
Write zero (used by Windows Vista and following windows versions)	1	zero

Table A2. US Department of Defense 5220.22-M Clearing and Sanitization Matrix

Media	Clear	Sanitize
Magnetic Tape1		
Type I	a or b	a, b, or m
Type II	a or b	b or m
Type III	a or b	m
Magnetic Disk		
Bernoullis	a, b, or c	m
USBs (floppys)	a or b	b or m
Non-Removable Rigid Disk	c	a, b, d , or m
Removable Rigid Disk	a, b, or c	a, b, d , or m
Optical Disk		
Read Many, Write Many	c	m
Read Only		m,n
Write Once, Read Many (Worm)		m, n
Memory		
Dynamic Random Access memory (DRAM)	c or g	c, g, or m
Electronically Alterable PROM (EAPROM)	i	j or m
Electronically Erasable PROM (EEPROM)	i	h or m
Erasable Programmable (ROM (EPROM)	k	l, then c, or m
Flash EPROM (FEPROM)	i	c then i, or m
Programmable ROM (PROM)	c	m
Magnetic Bubble Memory	c	a, b, c, or m
Magnetic Core Memory	c	a, b, e, or m
Magnetic Plated Wire	c	c and f, or m
Magnetic Resistive Memory	c	m
Nonvolatile RAM (NOVRAM)	c or g	c, g, or m
Read Only Memory ROM		m
Static Random Access Memory (SRAM)	c or g	c and f, g, or m
Equipment		
Cathode Ray Tube (CRT)	g	q
Printers		
Impact	g	p then g
Laser	g	o then g

a) Degauss (Type I) **b)** Degauss (Type II) **c)** Overwrite all addressable locations with a single character **d)** Overwrite all addressable locations with a character, its complement, then a random character and verify (NOT APPROVED FOR SANITIZING MEDIA CONTAINING TOP SECRET INFORMATION) **e)** Overwrite all addressable locations with a character, its complement, then a random character **f)** Each overwrite must reside in memory for a period longer than the classified data resided **g)** Remove all power to include battery power **h)** Overwrite all locations with a random pattern, all locations with binary zeros, all locations with binary ones **i)** Perform a full chip erase as per manufacturer's data sheets **j)** Perform i, then c, a total of three times **k)** Perform an ultraviolet erase according to manufacturer's recommendation **l)** Perform k, but increase time by a factor of three **m)** Destroy - Disintegrate, incinerate, pulverize, shred, or melt **n)** Destruction required only if classified information is contained **o)** Run five pages of unclassified text (font test acceptable) **p)** Ribbons must be destroyed. Platens must be cleaned **q)** Inspect and/or test screen surface for evidence of burned-in information. If present, the cathode ray tube must be destroyed.

Table A3. Inventory data used for the lifecycle assessment of enterprise servers (excluding electronic components).

Component/ Material	Name of for LCA	Data source
Aluminum	Aluminium mix IAI (2010) IAI (International Aluminum Institute)	PE-GaBi, International Aluminum Institute
Aluminum secondary	RER: aluminium, secondary, from old scrap, at plant	Ecoinvent
Acrylonitrile-butadiene-styrene (ABS)	RER: ABS co-polymer, at plant	Ecoinvent
Acrylonitrile-butadiene-styrene (ABS) secondary	EU-27: ABS plastic granulate secondary	PE-GaBi
Battery (coin cell CR2032)	GLO: coin cell(Li/Poly-carbonmonofluoride)	PE-Gabi
Battery (Li ion prismatic)	CN: single cell, lithium-ion battery, lithium manganese oxide/graphite, at plant	Ecoinvent
Brass	CH: brass, at plant	Ecoinvent
Brass, secondary	EU-27: Brass (CuZn20) from brass scrap	PE-GaBi
Cables (PSU)	EU-27: Copper Wire Mix DKI/ECI	PE-GaBi
Cardboard	RER: corrugated board base paper, kraftliner, at plant	Ecoinvent
Copper, primary	DE: Copper mix (99.999% from electrolysis)	PE-GaBi
Copper, secondary	SE: copper, secondary, from electronic and electric scrap recycling, at refinery	Ecoinvent
Electricity	EU-27 electricity grid mix	PE-GaBi
Ethylene vinyl acetate (PSU)	RER: ethylene vinyl acetate copolymer, at plant	Ecoinvent
Ferrous metals	DE: Steel sheet (ECCS) BUWAL	Ecoinvent
Glass fiber	DE Glass fibres	PE-GaBi
Gold, primary	SE: gold, from combined metal production, at refinery	Ecoinvent
Gold, secondary	SE: gold, secondary, at precious metal refinery	Ecoinvent
Magnet (HDD)	CN: neodymium oxide, at plant	Ecoinvent
Nickel, primary	GLO: nickel, 99.5%, at plant	Ecoinvent
Nickel, secondary	SE: nickel, secondary, from electronic and electric scrap recycling, at refinery	Ecoinvent
Palladium, primary	ZA: palladium, primary at refinery (50%), and RU: palladium, primary, at refinery	Ecoinvent
Palladium, secondary	SE: palladium, secondary at precious metals refinery	Ecoinvent
Polybutylene terephthalate (PBT)	Polybutylene terephthalate (PBT)	Stanford Research Institute, Ecoinvent
Polycarbonate	EU-25: Polycarbonate granulate (PC)	PE-GaBi
Polyethylene High Density (HDPE)	DE: Polyethylene High Density Granulate (HDPE) Mix	PE-GaBi
Polystyrene (GPPS)	EU-27: General purpose polystyrene (GPPS)	PE-GaBi
Polyurethane (PU)	RER: Polyurethane flexible foam (PU)	PE-GaBi
Polyvinylchloride (PVC)	RER: Polyvinylchloride injection moulding part (PVC)	PE-GaBi
Silver, primary	GLO: Silver, from copper production, at refinery	Ecoinvent
Silver, secondary	SE: Silver, secondary, at precious metals refinery	Ecoinvent

Component/ Material	Name of for LCA	Data source
Steel, primary	DE: Steel sheet (ECCS) BUWAL	Ecoinvent
Steel, secondary	DE: Steel sheet secondary (ECCS) BUWAL	Ecoinvent
Styrene-Butadiene Rubber (SBR)	DE: Styrene-Butadiene Rubber (SBR) mix	PE-GaBi
Thermal energy	Eu-27 natural gas mix	PE-GaBi
Water	EU-27 tap water	PE-GaBi
Zinc, primary	RER: zinc, primary, at regional storage	Ecoinvent

Table A4. Inventory data used for the lifecycle assessment of printed circuit boards contained in enterprise servers.

Components in PCBs	Name of process in GaBi database used for LCA	Data source for quantification in PCBs
Capacitors		
Al capacitor radial THT (D18 x 40)	Capacitor Al capacitor radial THT (15.41g) D18 x 41	Estimated based on (Fujicon, 2012)
Al capacitor radial THT (D13 x30)	Capacitor Al capacitor radial THT (5.65g) D12.5 x30	Estimated based on (Fujicon, 2012)
Al capacitor radial THT (110mg)	Capacitor Al capacitor radial THT (110mg)	Estimated based on (Fujicon, 2012)
Al capacitor SMD D3 x 5	Capacitor Al capacitor SMD (80mg) D3 x 5.4	Estimated based on (Fujicon, 2012)
Al capacitor SMD D6 x 5	Capacitor Al capacitor SMD (300mg) D6.3 x 5.4	Estimated based on (Fujicon, 2012)
Capacitor ceramic MLCC 0.4 x 0.2	Capacitor ceramic MLCC 01005 (0.054mg) precious metals 0.4 x 0.2	Estimated based on (GMC02, 2005)
Capacitor ceramic MLCC 0.6 x 0.3	Capacitor ceramic MLCC 0201 (0.17mg) precious metals 0.6 x 0.3	Estimated based on (GMC02, 2005)
Capacitor ceramic MLCC 1.6 x 0.8	Capacitor ceramic MLCC 0603 (6mg) precious metals 1.6 x 0.8	Estimated based on (GMC02, 2005)
Capacitor ceramic MLCC 3.2 x 3.2	Capacitor ceramic MLCC 1210 (50mg) precious metals 3.2 x 3.2	Estimated based on (GMC02, 2005)
Capacitor ceramic MLCC 5.7 x 5.0	Capacitor ceramic MLCC 2220 (450mg) precious metals 5.7 x 5.0	Estimated based on (GMC02, 2005)
Capacitor Tantal (7 x 4)	Capacitor Tantal SMD E (500mg) 7.3 x 4.3 x 4.1	Not available
Coils		
Coil miniature wound D9.8 x 5.7	Coil miniature wound SDR1006 (1.16g) D9.8 x 5.8	Assumption (copper content 20%)
Coil miniature wound D3 x2	Coil miniature wound SDR0302 (81mg) D3 x2.5	Assumption (copper content 20%)
Coil quad/chokes (14.5 x 13.3)	Coil quad/chokes (2.5g) 14.5 x 13.3 x 8	Assumption (copper content 20%)
Ring core coil (8g) - with housing	Ring core coil (8g) - with housing	Assumption (copper content 20%)
Ring core coil (30g) - with housing	Ring core coil (30g) - with housing	Assumption (copper content 20%)
Ring core coil (80g) - with housing	Ring core coil (80g) - with housing	Assumption (copper content 20%)
Ring core coil (8g) - without housing	Ring core coil (8g) - without housing	Assumption (copper content 25%)
Ring core coil (30g) - without housing	Ring core coil (30g) - without housing	Assumption (copper content 25%)
Ring core coil (80g) - without housing	Ring core coil (80g) - without housing	Assumption (copper content 25%)

Components in PCBs	Name of process in GaBi database used for LCA	Data source for quantification in PCBs
Integrated circuits		
SO		
IC, SO8	SO8(80mg) 4.9x3.9x1.7	SOIC 8 (4.9 x 3.9) gold wire (Spansion, 2015)
IC, SO14	SO8(80mg) 4.9x3.9x1.8	SO 14 (STM electronics 2010)
IC, SO16	SO20(500mg) 12.8x7.5x2.2	SOIC16 copper wire (Microchip, 2006)
IC, SO20	SO20(500mg) 12.8x7.5x2.3	SOIC16 copper wire (7.5 x 10.3) (Spansion, 2015)
IC, SO26	SO20(500mg) 12.8x7.5x2.3	SOIC16 copper wire (7.5 x 10.3) (Spansion, 2015)
IC, SO28	SO20(500mg) 12.8x7.5x2.3	SOIC16 copper wire (7.5 x 10.3) (Spansion, 2015)
SSOP		
IC, SSOP14	SSOP14 (120mg)6x5.3x1.75	SSOP14 (6.2 x 5.3 x 1.73) (IDT, 2006)
IC, SSOP20	SSOP24 (210mg)8.2x5.3x1.74	SSOP20 (Microchip, 2006)
IC, SSOP24	SSOP24 (210mg)8.2x5.3x1.75	SSOP24 (Microchip, 2006)
IC, SSOP28	SSOP24 (210mg)8.2x5.3x1.75	SSOP28 (Microchip, 2006)
IC, SSOP64	IC SSOP 64 (340mg) 26x10.2x1.75	SSOP64 (IDT, 2008)
TSSOP		
IC, TSSOP8	TSSOP8 (28mg) 3x2.9x1.2 DRAM	TSSOP8 (3 x 3 x 0.97) (IDT, 2009)
IC, TSSOP14	TSSOP16 (65mg) 4.4 x 5 DRAM	TSSOP14 (Microchip, 2006)
IC, TSSOP16	TSSOP16 (65mg) 4.4 x 5 DRAM	TSSOP14 (Microchip, 2006)
IC, TSSOP48	IC TSSOP 48 (102mg) 6.1x12.5x1.2 DRAM	TSSOP 48 (Pericom, 2010)
IC, TSSOP52	IC TSSOP 48 (102mg) 6.1x12.5x1.2 DRAM	TSSOP 48 (Pericom, 2010)
TSOP		
IC, TSOP32	IC TSOP 32 (325mg) 8x20x1.2 DRAM	TSOP40 Gold wire (18.4 x 10) (Spansion, 2015)
IC, TSOP44	IC TSOP 56 (590mg) 14x20x1.2 DRAM	TSSOP48 (Pericom, 2010)
IC, TSOP 56	IC TSOP 56 (590mg) 14x20x1.2 DRAM	TSOP56 Gold wire (Spansion, 2015)
IC, TSOP 59	IC TSOP 56 (590mg) 14x20x1.2 DRAM	TSOP56 Gold wire (Spansion, 2015)

Components in PCBs	Name of process in GaBi database used for LCA	Data source for quantification in PCBs
Integrated circuits		
QFP		
IC, QFP160	QFP80 (1.6g)14x20x2.7	TQFP 100 (14x14) Copper-Palladium wire Ni/Mg/Si frame (Atmel, 2014)
TQFP		
IC, TQFP44	IC TQFP 44 (260mg) 10x10x1.0	TQFP44 1 mm leadframe Copper alloy Gold wire (Cypress)
IC, TQFP80	IC TQFP 100 (520mg) 14x14x1.0	TQFP 100 (14x14) Copper-Palladium wire Ni/Mg/Si frame (Atmel, 2014)
IC, TQFP100	IC TQFP 100 (520mg) 14x14x1.0	TQFP 100 (14x14) Copper-Palladium wire Ni/Mg/Si frame (Atmel, 2014)
PLCC		
PLCC20	PLCC20 (700mg) 8.9x8.9x3.8	PLCC20 (9x9) (IDT, 2010)
DIP		
IC, DIP24	IC, DIP 24 (2.59 g) 35.5 x 8.2 x 3.8	Not available
BGA		
IC, BGA48	IC BGA48 (70mg) 6 x 6 x 1.1mm MPU generic	BGA 6 x 6 (Spansion, 2015)
IC, BGA (22 x 22)	IC BGA 256 (2.62 g) 27 x 27	Molded BGA 27mm full matrix (BG256) (Xilinx, 2007)
IC, BGA (27 x 27)	IC BGA 256 (2.62 g) 27 x 27	Molded BGA 27mm full matrix (BG256) (Xilinx, 2007)
IC, BGA (35 x 35)	IC BGA 672 (4.928 g) 35 x 35	Estimated based on Molded BGA 27mm full matrix (BG256) (Xilinx, 2007)
LGA		
IC, LGA (30 x 30)	IC LGA 1366 (42 x 42)	Estimated based on Molded BGA 27mm full matrix (BG256) (Xilinx, 2007)
IC, LGA (42 x 42)	IC LGA 1366 (42 x 42)	Estimated based on Molded BGA 27mm full matrix (BG256) (Xilinx, 2007)
LED		
LED SMD	LED SMD high-efficiency with lens max 0.5A (59mg) Au bond wire 3.5 x 3.5 x 2.0	Not available
LED SMD Flip chip	LED SMD high-efficiency with lens max 1A (60mg) Flip chip	Not available
LED THT 5 mm	LED THT 5 mm (350 mg) D5 x7	Not available

Components in PCBs	Name of process in GaBi database used for LCA	Data source for quantification in PCBs
PCB substrate		
PCB chassis	Printed wiring board 1 layer rigid FR4 with HASL finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB ODD	Printed wiring board 1 layer rigid FR4 with HASL finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB Expansion card	PWB 6 layers: based on PWB 4 and PWB 2 with chem-elec AuNi finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB HDD	Printed wiring board 4 layer rigid FR4 with chem-elec AuNi finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB PSU	Printed wiring board 2 layer rigid FR4 with HASL finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB Main board	PWB 6 layers: based on PWB 4 and PWB 2 with chem-elec AuNi finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
PCB raid key	Printed wiring board 1 layer rigid FR4 with HASL finish (substractive method)	Estimated based on (PCB Pool, 2015) and (Bourns, 2005)
Resistors		
Resistor THT (D4.0 x 11)	Resistor THT MBE 0414 (700 mg) D4.0 x 11.9	Not available
Resistor THT (D2.5 x 6)	Resistor THT MBB 0207 (220 mg) D2.5 x 6.3	Not available
Resistor THT (D1.6 x 3)	Resistor THT MBA 0204 (125 mg) D1.6 x 3.6	Not available
Resistor MELF (D2.2 x 5)	Resistor MELF MMB 0207 (79 mg) D2.2 x 5.8	Not available
Sockets		
USB type A	Connector, computer, peripherial type	USB type A (TE Connectivity, 2015)
USB type B	Connector, computer, peripherial type	USB B R/A (TE Connectivity, 2011)
PCI/DDR connectors	Connector PCI bus	PCI (TE Connectivity, 2014)
VGA connectors	Connector, computer, peripherial type	VGA (TE Connectivity, 2014)
CPU socket	Not available	LGA 1366 socket (TE Connectivity, 2015)

Components in PCBs	Name of process in GaBi database used for LCA	Data source for quantification in PCBs
Transistors		
Transistor SOT23 3 (1.5x3)	Transistor signal SOT23 3 leads (10mg) 1.4x3x1	SOT23 3 L (Microchip, 2006)
Transistor SOT23 3 (3x7)	Transistor signal SOT23 3 leads (110mg) 3.8 x 7.65 x 2.3	Not available
Transistor SOT23 3 (3 x 7)	Transistor signal SOT23 8 leads (180mg) 3.8 x 7.65 x 3	Not available
Transistor SOT93 (15 x13)	Transistor power THT/SMD SOT93/to218 7 leads (4.80g) 15.5 x 12.9 x 4.7	Not available
Transistor DPAK TO252 (6.5 x 6)	Transistor DPAK TO252 (290mg) 6.6 x 6.2 x 2.3	Not available
Others		
Switch	Key switch tact (242 mg) 6.2 x 6.3 x 1.8	Not included
Oscillator (11 x 5)	Oscillator crystal (500mg) 11.05 x 4.65 x 2.5	Not included
Diode (1 x 0.7)	Diode signal SOD123/323/523 (1.59mg) 0.8 x 0.75 x1.6	Not included

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Table A5. Recyclability rate of an enterprise server assuming EoL scenario 2.

Product Details					
Product	Mass (m) of the product [g]				
Enterprise server	27 799				
Parts for selective treatment:					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
Batteries	Coin cell(CR2032)	1.600	45%	0.720	IEC 62635 (Other battery)
	Li ion prismatic	43.000	45%	19.350	IEC 62635 (Other battery)
Main board	Aluminum	210.330	5%	9.465	Groot and Van der Linde, 2009
	Copper	310.043	95%	294.541	Huisman, 2003
	Iron	2.420	5%	0.121	Groot and Van der Linde, 2009
	Gold	0.225	98%	0.221	Rotter and Chancerel, 2012
	Lead	0.002	95%	0.002	Huisman, 2003
	Nickel	0.380	83%	0.315	Rotter and Chancerel, 2012
	Palladium	0.243	99%	0.241	Rotter and Chancerel, 2012
	Silver	0.247	99%	0.245	Rotter and Chancerel, 2012
	Tin	4.440	52%	2.309	Rotter and Chancerel, 2012
Memory cards	Copper	45.533	95%	43.256	Huisman, 2003
	Gold	0.225	98%	0.221	Rotter and Chancerel, 2012
	Nickel	0.194	83%	0.161	Rotter and Chancerel, 2012
	Palladium	0.021	99%	0.020	Rotter and Chancerel, 2012
	Silver	0.095	99%	0.094	Rotter and Chancerel, 2012
	Tin	2.840	52%	1.477	Rotter and Chancerel, 2012
Expansion card	Aluminum	12.2	5%	0.549	Groot and Van der Linde, 2009
	Copper	42.217	95%	40.106	Huisman, 2003
	Iron	0.690	5%	0.035	Groot and Van der Linde, 2009
	Gold	0.063	98%	0.062	Rotter and Chancerel, 2012
	Nickel	0.094	83%	0.078	Rotter and Chancerel, 2012
	Palladium	0.039	99%	0.039	Rotter and Chancerel, 2012
	Silver	0.052	99%	0.051	Rotter and Chancerel, 2012
	Tin	1.220	52%	0.634	Rotter and Chancerel, 2012
Cables	Brass	7.000	95%	6.650	IEC 62635 (Other metal)
	Copper	81.000	95%	76.950	IEC 62635 (Copper)
	Zinc	96.000	70%	67.200	IEC 62635 (Other metal)
	Plastics (HDPE)	104.000	94%	97.760	IEC 62635 (PE copolymer)
	Plastics (PVC)	145.000	0%	0.000	IEC 62635 (other polymer)
	PUR	2.000	0%	0.000	IEC 62635 (other polymer)
	Synthetic rubber	35.000	0%	0.000	IEC 62635 (other polymer)

Parts for selective recycling:					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$* RCR_i) [g]	References/details for the (RCR)
CPUs	Copper	30.500	95%	28.975	Huisman, 2003
	Gold	0.400	98%	0.392	Rotter and Chancerel, 2012
Heat pipes for CPU	Steel	140.000	95%	133.000	IEC 62635 (steel)
	Copper	442.000	95%	419.900	Average from IEC 62636 (copper)
2PSU	Aluminum	226.116	93%	210.288	Average from IEC 62636 (aluminum)
	Steel	1 346.000	95%	1 278.700	IEC 62635 (Steel)
	Plastic (EVA)	75.000	0%	0.000	IEC 62635 (other polymer)
	Plastic (PCFR40)	51.000	0%	0.000	IEC 62635 (other polymer)
	Fan				
	Copper	12.628	95%	11.997	Average from IEC 62636 (copper)
	Iron based	8.932	70%	6.252	IEC 62635 (Other metal)
	Steel	62.832	95%	59.690	IEC 62635 (steel)
	Plastic (PBT-GF30)	33.572	0%	0.000	IEC 62635 (other polymer)
	Plastic (PC ABS)	35.882	0%	0.000	IEC 62635 (other polymer)
	PCB				
	Copper	227.470	60%	136.482	Huisman, 2003; Ardente, Mathieux 2012
	Aluminum	111.250	5%	5.563	Groot and Van der Linde, 2009
	cables	30.834	0.24	7.400	IEC 62635 (cable, low current)
HDD	Aluminum	786.600	95%	747.270	IEC 62635 (Aluminum)
	Steel	547.124	95%	519.768	IEC 62635 (Steel)
	Ferrous based	152.076	70%	106.453	IEC 62635 (Other metal)
	Copper	6.992	95%	6.642	IEC 62635 (Copper)
	Magnets	68.172	0%	0.000	UNEP, 2013
	PCB				
	Copper	31.606	60%	18.964	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.044	26%	0.011	Rotter and Chancerel, 2012
	Iron	0.450	70%	0.315	IEC 62635 (other metal)
	Lead	0.001	60%	0.001	Huisman, 2003; Ardente, Mathieux 2012
	Nickel	0.100	25%	0.025	Rotter and Chancerel, 2012
	Palladium	0.079	26%	0.020	Rotter and Chancerel, 2012
	Silver	0.066	11%	0.007	Rotter and Chancerel, 2012
	Tin	0.870	39%	0.339	Rotter and Chancerel, 2012
	Plastic (PC/ABS)	68.172	0%	0.000	IEC 62635 (PCABS with additives)
	Plastic (PCGF)	52.440	0%	0.000	IEC 62635 (PC with/without additives)
4 Fans	Copper	77.572	95%	73.693	IEC 62635 (Copper)
	Iron based	54.868	70%	38.408	IEC 62635 (other metals)
	Steel	385.968	95%	366.670	IEC 62635 (Steel)
	Plastic (PBT-GF30)	206.228	0%	0.000	IEC 62635 (other polymer)
	Plastic (PC ABS)	220.418	0%	0.000	IEC 62635 (PC ABS)

Parts for selective recycling:					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
ODD	Aluminum	1.000	95%	0.950	IEC 62635 (Aluminum)
	Copper	7.000	95%	6.650	IEC 62635 (Copper)
	Low alloyed steel	115.000	95%	109.250	IEC 62635 (Steel)
	Plastics (ABS)	12.000	74%	8.880	IEC 62635 (ABS)
	Plastics (HDPE)	28.000	0%	0.000	IEC 62635 (HDPE)
	Plastics (PC)	7.000	0%	0.000	IEC 62635 (PC)
	PCB[2]				
	Copper	4.454	60%	2.672	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.002	26%	0.001	Rotter and Chancerel, 2012
	Palladium	0.000	26%	0.000	Rotter and Chancerel, 2012
	Silver	0.002	11%	0.000	Rotter and Chancerel, 2012
	Tin	0.005	39%	0.002	Rotter and Chancerel, 2012
	Solder	2.000	70%	1.400	IEC 62635 (Other metal)
Packaging	Cardboard	3 629.000	0%	0.000	IEC 62635 (others)
	HDPE	78.000	0%	0.000	IEC 62635 (others)
	Styrofoam	1 026.000	0%	0.000	IEC 62635 (others)
Other parts (for material separation):					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
Chassis	Aluminium	249.000	91%	226.590	IEC 62635 (Aluminum)
	Copper	179.000	85%	152.150	IEC 62635 (Copper)
	Steel	12 265.000	94%	11 529.100	IEC 62635 (Steel)
	Plastics (ABS)	348.000	74%	257.520	IEC 62635 (ABS)
	Plastics (PC)	282.000	0%	0.000	IEC 62635 (PC)
	Electronic components				
	Copper	13.472	60%	8.083	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.003	26%	0.001	Rotter and Chancerel, 2012
	Nickel	0.010	25%	0.003	Rotter and Chancerel, 2012
	Palladium	0.016	26%	0.004	Rotter and Chancerel, 2012
	Silver	0.021	11%	0.002	Rotter and Chancerel, 2012
	Tin	0.038	39%	0.015	Rotter and Chancerel, 2012
Sum of recyclable parts (S $m_{recyc,i}$ * RCR_i) [g]				17,143	
Recyclability rate ($R^{*}cyc$) [%]				61.7%	

Table A6. Recyclability rate of an enterprise server assuming EoL scenario 3.

Product Details					
Product		Mass (m) of the product [g]			
Enterprise server		27,799			
Other parts (for material separation):					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
CPUs	Copper	30.500	60%	18.300	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.400	26%	0.104	Rotter and Chancerel, 2012
Main board	Aluminum	210.330	5%	10.517	Groot and Van der Linde, 2009
	Copper	310.043	60%	186.026	Huisman, 2003; Ardente, Mathieux 2012
	Iron	2.420	5%	0.121	Groot and Van der Linde, 2009
	Gold	0.225	26%	0.059	Rotter and Chancerel, 2012
	Lead	0.002	60%	0.001	Huisman, 2003; Ardente, Mathieux 2012
	Nickel	0.380	25%	0.095	Rotter and Chancerel, 2012
	Palladium	0.243	26%	0.063	Rotter and Chancerel, 2012
	Silver	0.247	11%	0.027	Rotter and Chancerel, 2012
	Tin	4.440	39%	1.732	Rotter and Chancerel, 2012
Memory cards	Copper	45.533	60%	27.320	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.225	26%	0.059	Rotter and Chancerel, 2012
	Nickel	0.1942	25%	0.049	Rotter and Chancerel, 2012
	Palladium	0.0206	26%	0.005	Rotter and Chancerel, 2012
	Silver	0.095	11%	0.010	Rotter and Chancerel, 2012
	Tin	2.84	39%	1.108	Rotter and Chancerel, 2012
Expansion card	Aluminum	12.2	5%	0.610	Groot and Van der Linde, 2009
	Copper	42.217	60%	25.330	Huisman, 2003; Ardente, Mathieux 2012
	Iron	0.69	5%	0.035	Groot and Van der Linde, 2009
	Gold	0.063	26%	0.016	Rotter and Chancerel, 2012
	Nickel	0.0937	25%	0.023	Rotter and Chancerel, 2012
	Palladium	0.038908	26%	0.010	Rotter and Chancerel, 2012
	Silver	0.052	11%	0.006	Rotter and Chancerel, 2012
	Tin	1.22	39%	0.476	Rotter and Chancerel, 2012
Cables	Brass	7.000	70%	4.900	IEC 62635 (Other metal)
	Copper	81.000	60%	48.600	Huisman, 2003; Ardente, Mathieux 2012
	Zinc	96.000	60%	57.600	IEC 62635 (Other metal)
	Plastics (HDPE)	104.000	0%	0.000	IEC 62635 (PE copolymer)
	Plastics (PVC)	145.000	0%	0.000	IEC 62635 (other polymer)
	PUR	2.000	0%	0.000	IEC 62635 (other polymer)
	Synthetic rubber	35.000	0%	0.000	IEC 62635 (other polymer)

Other parts (for material separation):					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
Heat pipes	Steel	140.00	94%	131.600	IEC 62635 (steel)
	Copper	442.00	60%	265.200	Average from IEC 62636 (copper)
2PSU	Aluminum	226.116	91%	205.766	Average from IEC 62636 (aluminum)
	Steel	1 346.00	94%	1 265.240	IEC 62635 (Steel)
	Plastic (EVA)	75.00	0%	0.000	IEC 62635 (other polymer)
	Plastic (PCFR40)	51.00	0%	0.000	IEC 62635 (other polymer)
	Fan				
	Copper	12.628	60%	7.577	Huisman, 2003; Ardente, Mathieux 2012
	Iron based	8.932	70%	6.252	IEC 62635 (Other metal)
	Steel	62.832	94%	59.062	IEC 62635 (steel)
	Plastic (PBT-GF30)	33.572	0%	0.000	IEC 62635 (other polymer)
	Plastic (PC ABS)	35.882	0%	0.000	IEC 62635 (PC ABS)
	PCB				
	Copper	227.470	60%	136.482	Huisman, 2003; Ardente, Mathieux 2012
	Aluminum	111.250	5%	5.563	Groot and Van der Linde, 2009
	cables	30.834	24%	7.400	IEC 62635 (cable, low current)
HDD	Aluminum	786.600	91%	715.806	IEC 62635 (Aluminum)
	Steel	547.124	94%	514.297	IEC 62635 (Steel)
	Ferrous based	152.076	70%	106.453	IEC 62635 (Other metal)
	Copper	6.992	60%	4.195	IEC 62635 (Copper)
	Magnets	68.172	0%	0.000	UNEP, 2013
	PCB				
	Copper	31.606	60%	18.964	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.044	26%	0.011	Rotter and Chancerel, 2012
	Iron	0.450	5%	0.023	Groot and Van der Linde, 2009
	Lead	0.001	60%	0.001	IEC 62635 (Other metal)
	Nickel	0.100	25%	0.025	Rotter and Chancerel, 2012
	Palladium	0.079	26%	0.020	Rotter and Chancerel, 2012
	Silver	0.066	11%	0.007	Rotter and Chancerel, 2012
	Tin	0.870	39%	0.339	Rotter and Chancerel, 2012
	Plastic (PC/ABS)	68.172	0%	0.000	IEC 62635 (ABS PC with/without additives)
	Plastic (PCGF)	52.440	0%	0.000	IEC 62635 (PC with/without additives)
4 Fans	Copper	77.572	60%	46.543	IEC 62635 (Copper)
	Iron based	54.868	70%	38.408	IEC 62635 (other metals)
	Steel	385.97	94%	362.810	IEC 62635 (Steel)
	Plastic (PBT-GF30)	206.23	0%	0.000	IEC 62635 (other polymer)
	Plastic (PC ABS)	220.42	0%	0.000	IEC 62635 (PC ABS)

Other parts (for material separation):					
Parts and materials		Mass ($m_{recycl,i}$) [g]	Recycling rate (RCR_i) [%]	($m_{recycl,i}$*RCR_i) [g]	References/details for the (RCR)
ODD	Aluminum	1.000	91%	0.910	IEC 62635 (Aluminum)
	Copper	7.000	60%	4.200	IEC 62635 (Copper)
	Low alloyed steel	115.000	94%	108.100	IEC 62635 (Steel)
	Plastics (ABS)	12.000	74%	8.880	IEC 62635 (ABS)
	Plastics (HDPE)	28.000	0%	0.000	IEC 62635 (HDPE)
	Plastics (PC)	7.000	0%	0.000	IEC 62635 (PC)
	PCB				
	Copper	4.454	60%	2.672	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.002	26%	0.001	Rotter and Chancerel, 2012
	Lead	0.0002	60%	0.000	IEC 62635 (Other metal)
	Nickel	0	25%	0.000	Rotter and Chancerel, 2012
	Palladium	0	26%	0.000	Rotter and Chancerel, 2012
	Silver	0.002	11%	0.000	Rotter and Chancerel, 2012
	Tin	0.005	39%	0.002	Rotter and Chancerel, 2012
	Solder	2.000	70%	1.400	IEC 62635 (Other metal)
Packaging	Cardboard	3 629.000	0%	0.000	IEC 62635 (others)
	HDPE	78.000	0%	0.000	IEC 62635 (others)
	Styrofoam	1026.000	0%	0.000	IEC 62635 (others)
Batteries	Coin cell(CR2032)	1.600	45%	0.720	IEC 62635 (Other battery)
	Li ion prismatic	43.000	45%	19.350	IEC 62635 (Other battery)
Chassis	Aluminum	249.000	91%	226.590	IEC 62635 (Aluminum)
	Copper	179.000	60%	107.400	IEC 62635 (Copper)
	Steel	12 265.000	94%	11 529.100	IEC 62635 (Steel)
	Plastics (ABS)	348.000	74%	257.520	IEC 62635 (ABS)
	Plastics (PC)	282.000	0%	0.000	IEC 62635 (PC)
	PCB				
	Copper	13.472	60%	8.083	Huisman, 2003; Ardente, Mathieux 2012
	Gold	0.003	26%	0.001	Rotter and Chancerel, 2012
	Nickel	0.010	25%	0.003	Rotter and Chancerel, 2012
	Palladium	0.016	26%	0.004	Rotter and Chancerel, 2012
	Silver	0.021	11%	0.002	Rotter and Chancerel, 2012
	Tin	0.038	39%	0.015	Rotter and Chancerel, 2012
Sum of recyclable parts (S $m_{recyc,i}$ * RCR_i) [g]				16 556	
Recyclability rate (*R*cyc*) [%]				59.6%	

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