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Material composition of complex components in WEEE

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Abstract

Waste Electrical and Electronic Equipment (WEEE) is the fastest growing waste stream with an annual growth rate ranging between 4-5 %. The WEEE shows a complex material composition containing both valuable materials, e.g. copper, ferrous metals, gold, and critical metals, but also hazardous materials like heavy metals, flame retardants, and organic pollutants. Inadequate recycling is environmentally very intensive and poses a risk to human health. The typical recycling process of WEEE can be divided into three successive process steps: collection, pre-treatment, and end-treatment. The aim of the master thesis is to determine the material composition of components from WEEE, which have a significant recycling potential but cannot be associated with any single homogeneous material. These components are classified as complex components. After taking the samples of selected component types, i.e. hard disk drives, power supply units, and fans, the complex components have been dismantled into structural parts by in-depth disassembly. The analytical procedure combines a complementary application of simple material identification analysis, e.g. nickel test, acidic test, swim/sink test, and ICP-OES as advanced analytical technique. The results show that in-depth disassembly and subsequent simple material identification analyses are suitable to determine and quantify fifteen different base metals, plastics, and material composites amounting to in average over 90% of the components' mass. ICP-OES is introduced for an analysis of materials found in very small concentrations, e.g. precious and critical metals. This is exemplified by analysing aluminium capacitors from motherboard PCB to determine and quantify trace elements. In conclusion, this developed procedure enables to portray changes of trends in material composition over time and to pinpoint these changes for specific parts of the complex components.

Kurzfassung

Elektroaltgeräte (EAG) umfassen den am schnellsten wachsenden Abfallstrom mit einer jährlichen Wachstumsrate zwischen 4-5%. Die EAGs haben eine komplexe Materialzusammensetzung und enthalten sowohl wertvolle Materialien als auch gefährliche Stoffe wie Schwermetalle, Flammschutzmittel und organische Schadstoffe. Unzulängliches Recycling ist sehr umweltschädlich und stellt ein Risiko für die menschliche Gesundheit dar. Der typische Recyclingprozess von WEEE kann in drei aufeinanderfolgende Prozessschritte unterteilt werden: Sammlung, Vorbehandlung, und Endbehandlung. Ziel der Masterarbeit ist die Bestimmung der Materialzusammensetzung von Bauteilen aus EAG, die ein signifikantes Recyclingpotential aufweisen, aber nicht zu homogenen Materialströmen zugeordnet werden können, sondern sind im Rahmen der Vorbehandlung zumeist als komplexe Bauteilen aussortiert werden. Nach der Probennahme wurden die komplexen Bauteile, wie z.B. Festplattenlaufwerke, Netzanschlussgeräte und Lüfter, mittels Tiefenzerlegung demontiert. Das analytische Verfahren kombiniert die komplementäre Anwendung einer einfachen Materialidentifikationsanalyse durch Nickel-Test, Säure-Test und Schwimm/Sink-Test sowie ICP-OES als fortgeschrittene analytische Technik. Die Ergebnisse zeigen, dass einfache Materialidentifikationsanalysen ausreichend sind, um fünfzehn verschiedene unedle Metalle, Kunststoffe und Materialverbunde mit insgesamt über 90% Massenanteil zu bestimmen. ICP-OES wird für die Analyse von Materialien mit sehr kleinen Konzentrationen angewendet, z.B. für Edel- und kritische Metalle. Dies wird beispielhaft durch die Analyse von Aluminiumkondensatoren aus PC Hauptleiterplatten zur Bestimmung von Spurenelementen demonstriert. Das vorgeschlagene analytische Verfahren ermöglicht neben der Bestimmung der Materialzusammensetzung auch das Nachverfolgen von langfristigen Trends in der Materialzusammensetzung von komplexen Bauteilen.

Sažetak

Otpadna električna i elektronička oprema (WEEE) je najbrže rastući otpadni tok s godišnjom stopom rasta u rasponu od 4-5%. WEEE pokazuje složeni sastav materijala koji sadrži vrijedne materijale, npr. bakar, željezo, plemenite i kritične metale, ali i opasne materijale poput teških metala, usporivača plamena i organskih zagađivača. Neodgovarajuća reciklaža je ekološki problematična i predstavlja rizik za zdravlje ljudi. Tipični proces recikliranja WEEE-a može se podijeliti u tri uzastopna procesa: sakupljanje, predobrada i završna obrada. Cilj ovog istraživanja je odrediti sastav materijala komponenti elektroničkog otpada, koji imaju značajan potencijal za recikliranje, ali ne mogu biti pridruženi niti jednom homogenom materijalu. Takve komponente elektroničkog otpada su klasificirane kao složene komponente. Nakon uzimanja uzoraka odabranih tipova komponenata koje čine tvrdi diskovi (eng. Hard Disk Drive), optički diskovi (eng. Optical Disc Drive), napojne jedinice, i ventilatori, složene komponente su demontirane na sastavne dijelove. Analitički postupak za utvrđivanje sastava materiala kombinira komplementarnu primjenu jednostavnih testova, npr. nikl test, kiselinski test, itd., i ICP-OES kao naprednu analitičku tehniku. Rezultati studije pokazuju da primjenom jednostavnih testova analize materijala je moguće identificirati i kvantificirati petnaest različitih materijala uključujući osnovne metale, plastiku i kompozite različitih materijala koji u prosjeku iznose više od 90% ukupne mase analiziranih složenih komponenti. ICP-OES analiza je korištena za materijale koji se nalaze u vrlo malim koncentracijama, npr. premeniti i kritični metali. Ovaj princip je prikazan analiziranjem aluminijskih kondenzatora s matične ploče iz osobnih računala. Prilikom analize su identificirani i kvantificirani elemenata u koncentracijama ispod 5000 ppm. Naposlijetku, primjenjivanjem predloženog postupka moguće je, pored sastava materijala, također utvrditi trendove promjena u sastavu materijala i te promjene pridružiti specifičnom elementu gdje se dogodila promjena.

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List of abbreviations

%RSD - Residual Standard Deviation [in %]
AC - Alternating current
BAT - Best Available Technique
BTEX - Benzene, toluene, ethylbenzene and xylenes
CPU - Central Processing Unit
CRM - Certified Reference Material
DC - Direct current
HBCD - Hexabromocyclododecane
LOD - Limits of Detection
LOQ - Limits of Quantification
N/A - Not available
ODD - Optical Disc Drive
PB - Process blank
PC - Personal Computer
PCB - Printed Circuit Beard
PCDD - Polychlorinated dibenzodioxins
PCDF - Polychlorinated dibenzofurane
PGMs - Platinum Group Metals
PHAH - Polyhydroxyalkanoates
PMs - Precious metals
PRML - Partial Response Maximum Likelihood
PSU - Power Supply Unit
REE - Rare Earth Elements
SMPS - Switching Mode Power Supply
SoC - System on Chip
TBBPA - Tetrabromobisphenol A
TetraBDE - Tetra-brominated diphenyl ether
TFC - Thermal Flight-Hight Control
TPC - Thermal Positioning Control
UHP - Ultra-High Purity water
VCA - Voice Coil Assembly
WEEE - Waste Electrical and Electronic Equipment
Wt.% - Weight percent (weight-weight percentage)
XRF - X-ray Fluorescence

1. Introduction

1.1 Quantity and significance of WEEE

The amount of Waste Electrical and Electronic Equipment (WEEE), also referred to as e-waste, in the year 2014 exceeded 40 million t globally with an annual growth rate ranging between 4-5 % (Baldé, 2015). Given the fact that the global population in 2014 was app. 7,266 billion people (Worldometers, 2017), the annual average of e-waste generation was 5,5 kg per capita. There are several convoluted factors influencing the generation of e-waste. First, there is a direct correlation between the increase in purchasing power (GDP PPP) and increase in demand for goods and services, which subsequently leads to the higher generation of waste. Second, the generation of e-waste was strongly influenced by rapid technological development in the past twenty years, making electronic devices obsolete after a very short period of time. Finally, another important, although not so conspicuous factor for e-waste generation is the population growth. The use of technology and access to the internet has become a necessity for normal functioning in the modern society and thus amplifies the already increasing demand for electronic devices.

Electronic equipment contains high levels of various environmental hazards. For example, the small household appliances (sHHA) subcategory of WEEE contains following average concentrations of heavy metals [mg/kg]: 210 Cd, 130 Co, 800 Ni, 1780 Pb, 310 Sn (Fu et al., 2008). Besides heavy metals, there is also a multitude of other hazardous components, such as flame retardants (TBBPA, HBCD, TetraBDE, etc.), organic hazards (BTEX, PAHs, PCBs, etc.), toner dust, liquid crystals (cf. Salhofer and Tesar, 2011). These substances are volatile and their disposal in landfills without prior treatment can cause various environmental and health problems. Such substances, which are hazardous in nature and directly originate from electronic devices, can be classified as “primary contaminants” (c.f. Khanna et al., 2014). Furthermore, emissions occur also during the treatment of e-waste, as a result of both formal and informal recycling. These emissions arising as side effects from treatment processes can be thus classified as “secondary contaminants”. For example, the shredding of e-waste releases dust containing cadmium, lead, PBDEs, TBBPA and other. The incineration/open burning and pyrometallurgical processing lead to heterogeneous emissions, which consist of volatile substances already contained within the devices prior to the treatment process, but also new hazardous compounds created as a side effect of the recycling process. Typical emissions arising from incineration processes include: PXDDs/Fs, PCDDs/Fs, PCDDs/Fsetc (Tsydenova and Bengtsson, 2011). Moreover, hydrometallurgical processing and acidic leaching are especially environmentally intensive. Side effects of these recycling processes include spent acids, sludges, nitrogen and chlorine emissions and other residuals containing heavy metals, PBDEs, PCBs and PAHs (Khanna et al., 2014).

In a traditional point of view, e-waste is primarily observed as an environmental problem. In the recent years, the e-waste has been increasingly regarded through the prism of geopolitics and distribution of natural resources. Since the components of electrical and electronic equipment (EEE) are made of a wide range of metals, the e-waste is more and more perceived as a resource sink rather than mere waste. Single devices, such as mobile phones, can contain over 20 different metals, many of which belong to the category of precious metals, such as Ag, Au, and Pd, (Schluep et al., 2009). The most valuable components in terms of material composition are printed circuit boards (most of all motherboards and mobile phone PCBs), integrated circuits, Hard Disk Drives, relays, cables and other. Although, the precious metal content in a single device is only in the order of up to couple of hundred milligrams, considering the sheer mass of the waste stream it can easily be stated that the significant reserves of valuable materials are contained in the e-waste stream.

1.2 Legal framework

Legal framework regulating the management of WEEE in the EU essentially relays upon two directives: Waste Electrical and Electronic Equipment Directive 2012/19/EU (WEEE Directive) and Restriction of Hazardous Substances Directive 2002/95/EC (RoHS). The directives became effective as of 2003 and 2006 respectively, and since then have had a decisive role in shaping the recycling market in the EU, European Economic Area (EEA), and beyond.

The WEEE directive addresses major aspects regarding WEEE management and it has undergone several changes since it has been introduced in the year 2002. The latest amendment became effective in 2012. Core elements of WEEE directive include classification of WEEE into relevant subcategories, determining compulsory collection rates and recycling rates and shipment of WEEE (cf.Salhofer et al., 2016, Huisman et al., 2007).

The amendment of WEEE directive from 2012 stipulates a transition of currently relevant ten categories of WEEE into six new subcategories from August 2018. The new categories are: 1) Temperature exchange equipment, 2) Screens and monitors, 3) Lamps; 4) Large equipment, 5) Small equipment and 6) Small IT and telecommunication equipment with external dimensions less than 50cm along the longest edge. Moreover, currently effective compulsory rate for separate collection of WEEE is set at 45% of the total EEE put on the market. The collection rate is calculated as ratio of the total weight of WEEE collected over the average weight of EEE put on the market in the three preceding years. Recycling targets are determined for each subcategory individually and they range between 55 – 85%.

Although the WEEE directive does not define or regulate particular process steps within the WEEE treatment process, the directive identifies certain substances, material mixtures, and components which have to be removed from any separately collected WEEE (Salhofer et al., 2016). Selective treatment is required among other for following components: capacitors containing polychlorinated biphenyls, mercury containing switches, batteries, printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimetres.

Despite those measures set out in the WEEE directive, experience shows that considerable amount of WEEE will be disposed of without optimal treatment. To this extent, heavy metals and flame retardants contained in the WEEE pose significant health and environmental risk. The RoHS directive addresses this problem by identifying and prohibiting the use of the most hazardous materials in the manufacture of WEEE. The materials covered by the RoHS directive are: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl ethers, and phthalates.

1.3 Overview of the recycling process

The recycling process of WEEE can be subdivided into three consecutive process steps: collection, pre-processing, and end-processing (see Figure 1). In general, each of the process steps is carried out by one or more separate specialized companies (Schluep et al., 2009). Furthermore, capital investment and technology requirements are expending significantly with each subsequent step of the recycling process. As consequence, the recycling process of WEEE is an international enterprise with a multitude of private and public stakeholders.

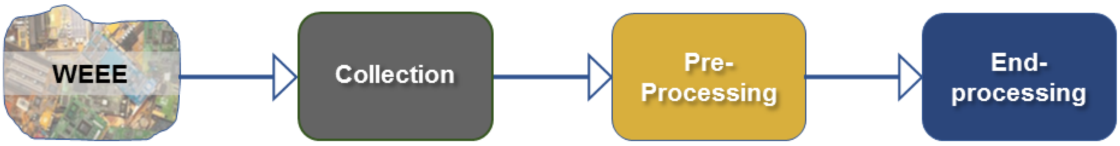


Figure 1: Overview of the recycling process of WEEE

Collection of WEEE is one of the crucial process steps for the effectiveness of the recycling process. However, compared to the other processes, technical solutions and infrastructure have a substantially weaker influence on the overall performance of the collection. To a large extent, the success of collection depends on societal and socio-economic factors (Huisman et al., 2008, Schluep et al., 2009). According to the status report of Environment Agency Austria (Umweltbundesamt) (2015) the overall collection rate for WEEE in Austria in the year 2015 was 48.5%. Also, it is approximated that an average efficiency of the pre-processing is 75% (Chancerel and Rotter, 2009). Finally, official reports claim that integrated smelters have an average efficiency level of 99% in the end-processing (cf. Hagelüken, 2006). Consequently, it can be concluded that the average efficiency of the whole recycling process is only 36%. Also, it is obvious to conclude that the collection, followed by the pre-processing, has the highest potential for further development.

The **pre-processing** process step usually includes following processes: de-pollution, mechanical treatment or mechanical size reduction, and sorting. Organization of the pre-processing is reasonably flexible, thus design and the extent of deployed equipment can significantly differ from one company to another. In Europe, there are two prevailing technologies applied for the de-pollution process. Namely, a manual dismantling where the devices are opened and both valuable and hazardous components are sorted out or an alternative approach where the devices are broken apart by mechanical processes and followed by manual sorting of both hazardous and valuable components along conveyor belts (Salhofer and Tesar, 2011). The de-pollution is followed by mechanical treatment, which usually includes one or more shredding steps for size reduction and separation of different materials. The resulting fractions from shredding process are separated by a series of different sorting processes. The form and extent of the sorting process can vary significantly depending on the input material, design of the mechanical treatment, legal requirements, and other technological and economic factors (cf. Habib Al Razi, 2016).

Outputs of the pre-processing process step can generally be subdivided into four output categories. First, hazardous components, e.g. batteries, switches, and capacitors, have to be sorted out to meet the legal requirements of WEEE directive. The hazardous components are removed either by manual dismantling directly from appliances or after a mechanical process which first breaks the appliances and then the hazardous components are sorted out manually along conveyor belts (Salhofer and Tesar, 2011). Second, valuable components and materials, which can be reused and/or sold on the market, are also sorted out from the rest of WEEE. The segregated portion of this waste stream is highly depending on the process configuration of a recycling company and type of input material. The third category is constituted of recyclable materials which will be subsequently sold to companies conducting material recovery (=end-processing). This waste stream usually includes fractions such as ferrous metals, aluminium, copper, plastics, etc. The fourth category covers non-hazardous materials that is not suitable for reuse or material recovery and will be disposed. For example, these are plastic foils, wood pieces, ceramics and other impurities that may negatively affect the process steps during pre-treatment.

The **end-processing** segment involves technologically intensive processes for final recovery of metals and plastics. Presently, the metal recovery is primarily carried out via pyrometallurgical processing and to a lower extent via hydrometallurgical processing (Cui and Zhang, 2008). Ferrous metals are transferred to steel smelters for recovery of iron, aluminium-rich fractions are sent to aluminium smelters and prevailingly copper material components, e.g. wires, and hazardous components, e.g. capacitors, PCBs, switches, etc., are directed to integrated smelters. The integrated smelters have the ability to recover up to 30 different metallic fractions from WEEE, while the emission of hazardous substances can be significantly reduced by the installation of filtration systems (Hagelüken and Corti, 2010). The pyrometallurgical processing is very capital intensive whereas the hydrometallurgical processing requires utilization of strong acids and thereby can have a considerable environmental impact. Therefore, a need for the development of alternative recovery method has emerged. The technologies, which have proved to have the highest potential so far for substituting or complementing the conventional methods for metal recovery are biometallurgy and electrometallurgy.

1.4 Objective of this thesis

The focus of this master's thesis is on components which have significant recycling potential, but due to their complex construction cannot be associated with any single (homogenous) material output stream like ferrous metals, aluminium, or similar. For all practical purposes from this point on these components will be referred to as just "complex components". The material stream containing complex components emerges primarily during the dismantling process or during the mechanical de-pollution process. Although complex components emerge also in the subsequent process steps as part of a shredder output stream, these components get fragmented and deformed, which makes the analysis considerably harder. Therefore, the complex components originating after the shredding process is not included within the system boundaries of this research. A general overview of the pre-treatment process with the focus of this research can be observed in the figure below (Figure 2).

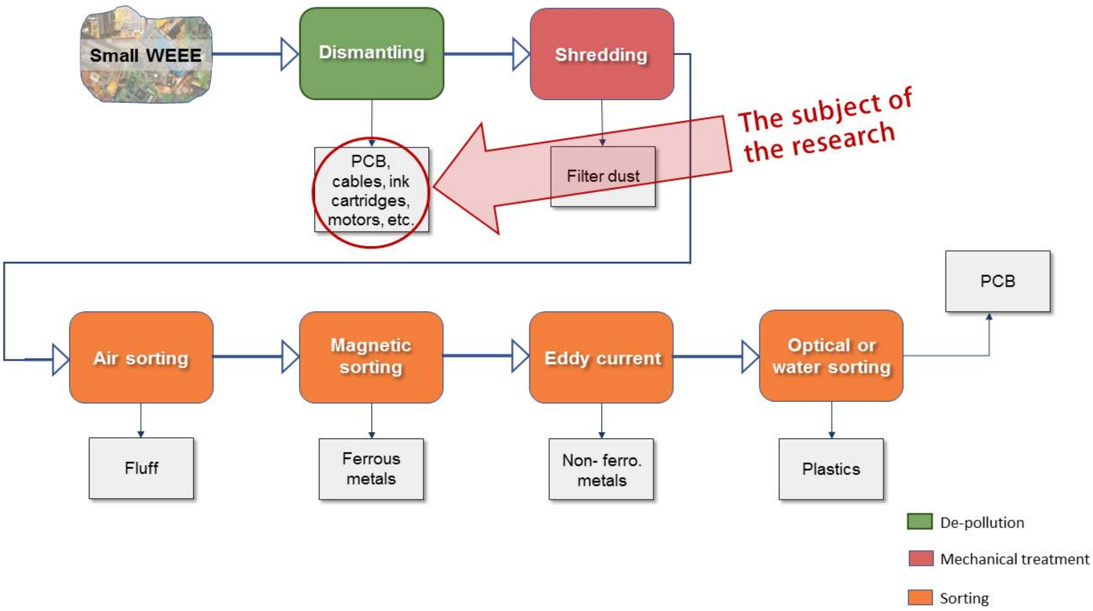


Figure 2: Overview of the pre-processing of WEEE

Economic performance of the pre-processing and the recycling efficiency of the end-processing are in direct correlation to a capability of the recycling company to segregate material output streams as homogenous as possible or as homogenous as it is economically feasible. The general rule for the pre-processing implies that the recovery rate of a particular metal is decreasing with an increasing inhomogeneity rate of that metal in the output material stream. In other words, the more complex material composition is, the lower the recycling efficiency. This means that the higher the scope of inclusiveness of a target metal is, the more "impurities" will end up in this output stream (cf. Chancerel et al., 2009, Hagelüken, 2006). Finally, the homogeneity of the output stream, alongside with current market prices of raw materials, will determine the market price of that output stream. Which materials will be considered as impurities depends on their concentration in the output stream and the final destination for the metal recovery. For example, precious metals (PM) in WEEE are generally concentrated in a copper fraction, but they are also strongly interlinked with other metals and plastics (Hagelüken, 2006). his means that besides plastics, also metals like Br, Pb, Cd, Cl are considered as impurities in the Cu-output stream. Similarly, Cu contained in the Fe or Al output fraction is considered as the impurity, since iron and aluminium smelters do not have a capability of Cu or PM recovery. In order to be able to optimize their operations, the pre-processing companies need accurate material composition databases for their target WEEE types and, if possible, a reliable and cheap analysis methods for input characterisation in order to close the gaps in the databases. In this way, an optimization and increase in efficiency of the entire recycling process would be possible by simpler assessment of the full potential of the material input stream and simultaneously allow more flexibility for the pre-processing companies.

The aim of the master thesis is to develop a suitable analytical procedure for a determination of the material composition of components from WEEE. In order to achieve this goal, a novel material identification procedure has been constructed based on simple ordinary tests for metal identification. The simple material analysis is combined with Inductively Coupled Plasma Optic Emission Spectroscopy (ICP-OES) analytical procedure to determine the concentrations of trace elements.

2. Data and methods

In the following chapter are technological development, functionality, and methods for the analysis of complex components from WEEE described. Availability of material compositions in the scientific literature and their economic significance, as the focus of the master's thesis following components, have been selected: hard disk drives, optical disc drives, power supply units from PCs and printers, and active fans. The samples have been taken at the local recycling company "Demontage Recycling Zentrum" (DRZ), which obtains the WEEE directly from civic amenity sites from the city of Vienna and surrounding area. After transportation to DRZ, the complex components have been randomly collected prior to any further treatment steps.

2.1 Technological development and functionality of complex components

2.1.1 Hard Disk Drive

It has been over 60 years since IBM introduced the first commercial computer equipped with a magnetic disk storage, i.e. the first hard disk drive (Ruemmler and Wilkes, 1994). In the year 2016, the total storage capacity was approx. 1,600 Exabytes worldwide with a growth rate of 40% per annum (IDC, 2014) and despite the development of new technologies, e.g. solid-state drive, computer clouding, etc., Hard Disk Drives (HDDs) have remained the dominant solution for data storing (see Figure 3).

The evolution of HDDs can be arbitrarily classified into four phases since they have been introduced for the first time. These four phases of technological development can be distinguished based on several key characteristics, e.g. design, storage capacity, and data storage density. The first phase lasted from the first commercial application until the 1991 and it is characterised by a large variety of design solutions varying from linear to rotary actuation, from ferrite to thin film heads, and from particulate to thin-film media. The main objective in this stage of development was to decrease dimensions and tolerances while maintaining the data storing efficiency (Wood, 2009). For the beginning of the second phase was taken the introduction of a magneto-resistive (MR) read/write head in the year 1991 (cf. Ruemmler and Wilkes, 1994). This is the also the time when HDD got their recognizable design, which prevails also today. As stated by Wood (2009) and Hattori et al. (2016), the period between the beginning of 1990-is until the mid-2000s was characterized by remarkable improvements in data storing efficiency by development of MR read/write head and giant magneto-resistive (GMR) read/write head, and the reduction of median noise, which is determined by the strength and the sharpness of the read/write head and the quality of the recording medium. The third and fourth phase are relatively shorter than the first two. The third phase begins approx. in the year 2000 by reaching the physical boundary of the longitudinal mode of recording. As a result, the increase of areal recording density decreased significantly (cf. Radding, 2010, Wood, 2009). As the beginning of the fourth phase was taken the introduction of a perpendicular mode of recording in the years between 2005 and 2007. The perpendicular recording is characterised by an orthogonal positioning of a magnetisation axis in relation to the platter surface and thus by making possible writing very sharp transitions into a thick and high-coercivity medium (Wood, 2009). As a result of this innovation, the areal recording density increased to approx. 50% per annum (see Figure 4).

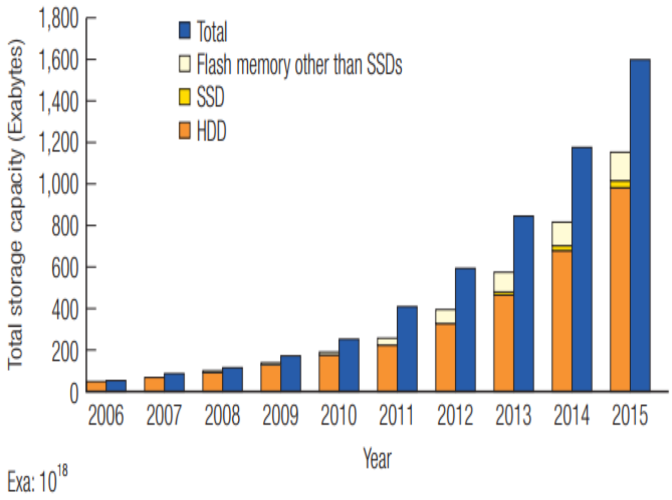


Figure 3: Overview of total digital data storage (Hattori et al., 2016)

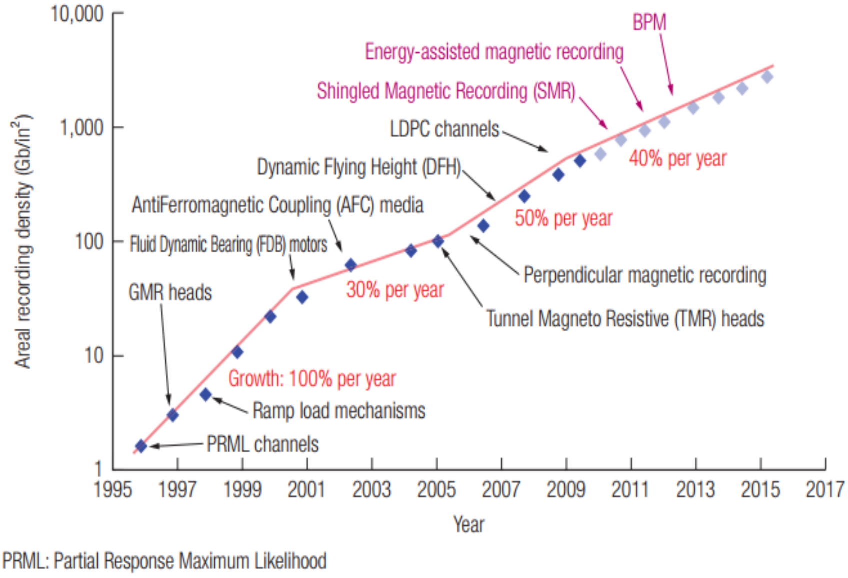


Figure 4: Storage modalities and recording density (Hattori et al., 2016)

The concept of HDD, developed in the beginning of 1990-is and is still in use, relies on the following principle. The core of HDD represents a recording medium on the surface of one or more quickly revolving platters. The data are stored and retrieved via read/write heads (one per surface). The platters are put in motion by a DC brushless motor, also called spindle motor. Approx. since the year 2000, oil bearings have been replaced by ball bearings in the spindle motor (Wood, 2009). The read/write heads are mounted on a comb-like actuator arm. The actuator arm is driven by a DC motor containing only a single coil, which is also called a voice-coil motor (VCM) (cf. Ruemmler and Wilkes, 1994, Wood, 2009). The actuator arm needs to be very light in order to reduce inertia during the rapid movements across the platters. The lower the weight of actuator arm is, the lower is the energy consumption and heat generation. However, the actuator also needs to be very stiff in order to increase the accuracy of track-following (Wood, 2009). So far, aluminium was the material of choice for the actuator arm, which meets all the listed prerequisites.

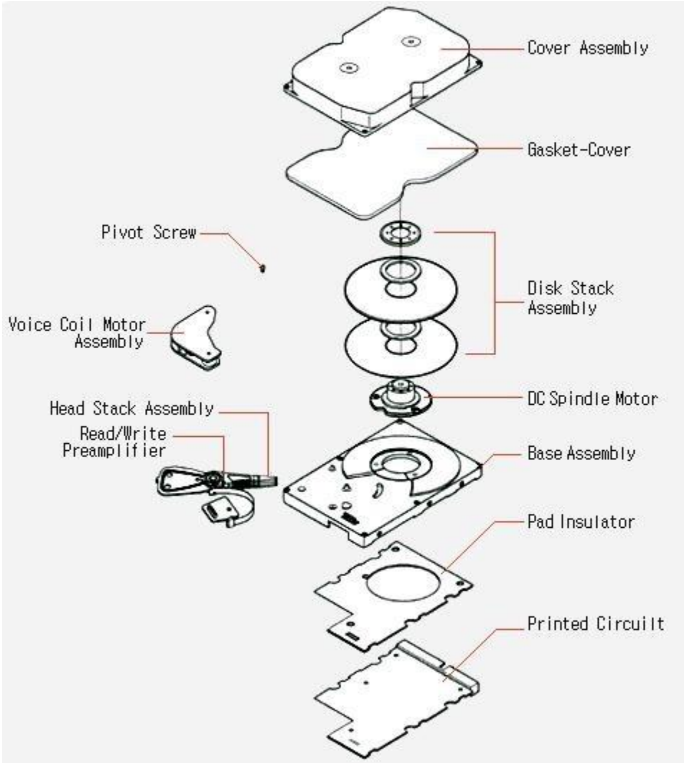


Figure 5: Structure of a HDD (Hsiung, 2009)

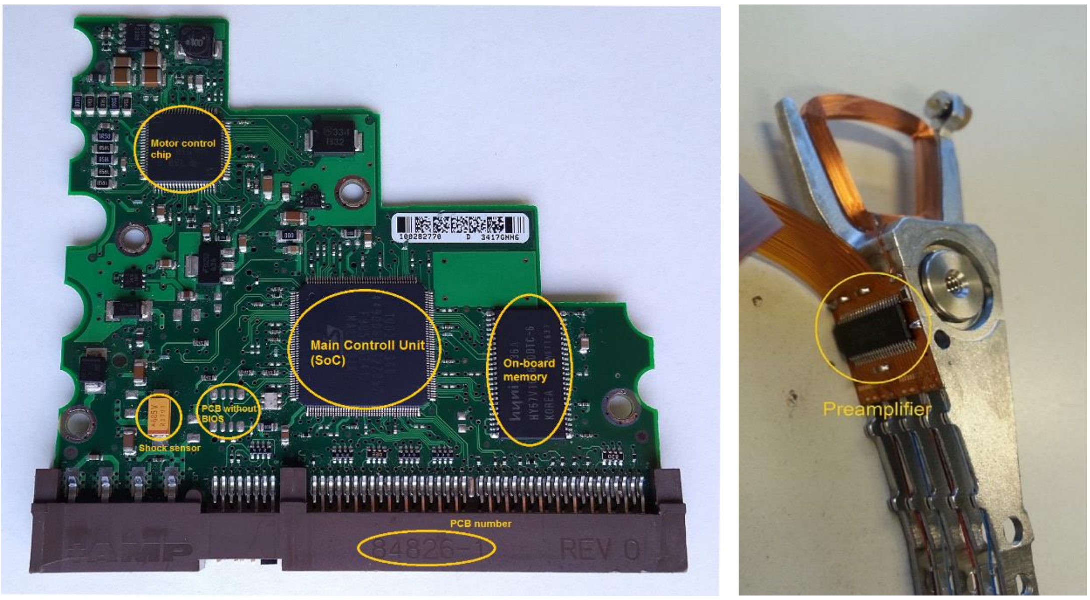


Figure 6: Key integrated circuits contained in a HDD

Technologically, the most complex part of the HDD is an air-bearing slider that carries the read/write elements only several nanometres above the surface of the platter. The clearance is determined by miniature resistive heaters on the slider via thermal expansion. The read/write head has two heaters. One heater, Thermal Positioning Control (TPC), is oriented parallel to the platter and regulates fine track following of the read/write head and moves in both horizontal and vertical direction. The other heater, Thermal Flight-Hight Control (TFC), is located perpendicular to the platter and regulates the clearance between the read/write head and the platter without moving in the horizontal direction (Atsumi, 2016).

HDD has three key integrated circuit (IC) components, i.e. preamplifier mounted on the actuator arm, motor driver, and a large “system-on-chip” (SoC). The last two IC are mounted on a printed circuit board (PCB) (Wood, 2009, Radding, 2010). The motor driver IC regulates the spindle motor, voice coil motor, and DC-DC converters. The SoC contains the hard-disk controller, a read/write channel and a high-speed interface with other components of a computer. Besides the key IC, HDDs contain also some solid-state memory, shock and vibration sensors, and other (Wood, 2009). A detailed overview of mounted IC in HDD is available in Figure 6.

2.1.2 Optical Disc Drive

Similarly, as it was the case with HDDs, the technology of optical data storing has undergone momentous development since a 12-inch LaserVision video disc, the first optical data storage medium was introduced in the year 1972 (McLoughlin, 2011). However, the technological development is more pronounced with an evolution of data storing discs than with the disc drives. Since LaserVision, four major storing formats have been developed, each superseding the previous in the storage capacity and the quality of reproduced data.

The 12-inch LaserVision video disc was superseded by an audio CD (Compact Disc) in the year 1980. The audio CD was developed by companies Philips and Sony and supports only audio data with maximum storage capacity of 74 – 80 min of reproduction time. The next innovation was the development of a CD-ROM (Compact Disc Read-Only Memory), an erasable and rewritable 5.25-inch optical disc drive. It was developed in the year 1987 by Sony Corporation (McLoughlin, 2011). The CD-ROM is very similar to the audio CD, but it can also support video and other types of files.

The next format in the evolution of optical data discs was a DVD (Digital Versatile Disc) format. The DVD was developed by three companies, i.e. Toshiba, Sony, and Panasonic, in the year 1995 (Taylor et al., 2006). It can store all available digital formats and offers significantly higher storage capacity while having the same dimensions as CD-ROM. Up to this time, the latest invention in the field of optical discs is the Blu-ray format. In the year 2000, Sony presented the first prototype of Blu-ray disc, but the broader commercial application of the Blu-ray begun until the mid-2000s (Blu-ray.com, 2017, Watson, 2014).

The Blu-ray format represents an improvement compared to the DVD format by higher data storage capacity and capability of supporting of the ultra-high definition videos. Optical discs have their application in a variety of different devices, e.g. CD players, gaming console, Walkman, PCs, etc. In the rest of the chapter, only optical disc drives (ODD) from PC will be further addressed.

From the structural point of view, the ODD has two mechanisms: a disc recording/reproducing mechanism also called the traverse mechanism and a loading mechanism. The recording/reproducing mechanism has a spindle motor, stepping motor, optical pickup head for recording and reproducing purposes, and other minor components mounted on a metal base. The loading mechanism can be further subdivided into tray mechanism and eject mechanism (Lee et al., 2009). The tray mechanism is a plastic substrate for the discs and eject mechanism makes their insertion and ejection from a drive possible.

Technologically, the most complex part of an ODD is the pickup head, which consists of a semiconductor laser, photodiodes for reading the light reflected from the disc, and lens for the laser beam focusing (Taylor et al., 2006, Stan, 1998). The recording process by encoding data on a recordable disc by selectively heating parts on a recording layer with a laser diode. The pickup head is settled on sliding rails that allow radial movement of the pickup head relative to the disc. A micro-stepping motor moves the pickup head along the sliding rails. A laser diode inside of the pickup head emits a beam, which is focused by the lens before reaching its final destination on a surface of the disc. By scaling the power of laser outburst, allows the ODD either to read the stored data using low power setting or record data on the disc at high power outburst (Butler, 2011, Taylor et al., 2006, Stan, 1998).

The loading process begins when the laser beam reaches the disc. It becomes partially dispersed as it hits lands and pits on the disc, which are created during the recording process. An optical pickup receives the reflected beam. The received signal is first transferred into binary code and then into bytes of data (Butler, 2011). The wave lengths of a laser eventually decreased from 780 nm for audio CD and CD-ROM, over 650 nm for DVDs, and finally to 405 nm for Blu-ray discs. However, these changes did not have a significant influence on the material composition of the pickup head (Watson, 2014).

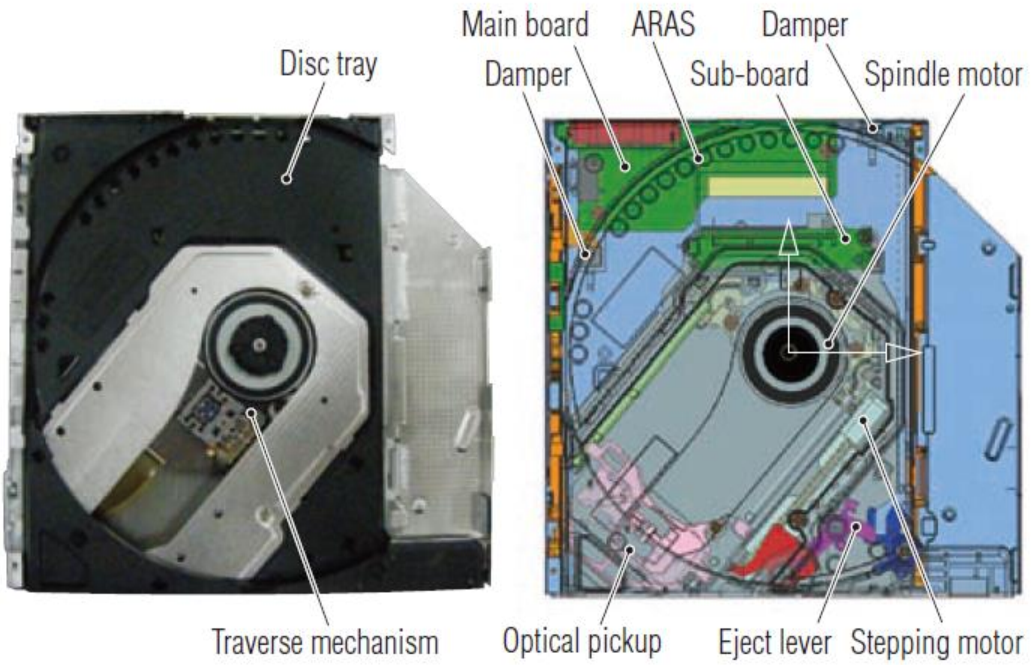


Figure 7: Structure of the ODD (Lee et al., 2009)

2.1.3 Power Supply Unit from PC (Switch Mode Power Supply)

The component responsible for supplying a PC with the electricity is a Power Supply Unit (PSU). The primary function of PSU is to convert the alternating current (AC), which is supplied by a public electrical grid, into direct current (DC) that is used by the electronic components in the PC (Torres, 2008). The AC from the public electrical grid has conventionally either 110 or 220 V alternating voltage, which is converted by the PSU into continuous voltages, +3.3 V, +5 V, +12 V, and -12 V, needed by the electronic components. The secondary function of PSU is a cooling process for the PC (Katzer, 2008, Torres, 2008).

There are two main types of PSU: linear power supply and Switch Mode Power Supply, usually referred just as SMPS. The linear power supplies are used for devices that have low-power demand, e.g. scanners, printers, cordless telephones, etc. An input alternating voltage is inversely proportional to the size of a transformer and the capacitances of an electrolytic capacitor in the PSU. This means that the higher the electricity demand is, the larger the transformer needs to be (Torres, 2006). Since the PCs have relatively high electricity demand, the PSU built in PC are always SMPS type, since the linear power supply would be unfeasibly large. Unlike HDDs and ODDs, the technology behind the SMPS has been consistent since the breakthrough of PCs, so that the changes in overall design and material composition have been influenced by the differences between lower quality SMPS and the higher quality SPMS.

Parallel to the development of electronic devices, over the years several standards of SMPS have been developed. The first PSU for PC has been developed by IBM in the year 1984 and was designated as AT standard (Advanced Technology). ATX (Advanced Technology Extended) superseded the AT standard. This model introduced improved connectors and better organisation of the components with respect to the airflow compared to the previous model. As an improvement of the ATX standard was EPS (Entry level Power Supply) standard developed. It is characterised by more power and higher efficiency compared to the predecessor. It is used for servers and more demanding PCs (Mpitziopoulos, 2015). A BTW (Balanced Technology Extended) is a standard, which coincided with the development of Pentium 4 PC. The most significant innovations associated with this standard are improved airflows and thereby the reduction of the temperature for the whole PC (Kirsch, 2005b). Besides these already mentioned standards, there are also further standards, which provided solutions for some more specific technological demands, e.g. smaller size (CFX), smaller computers (SFX), or computers with flat housing (TFX) (Mpitziopoulos, 2015).

The PSU from PC has following components: cables, housing, PCB, and an active fan. The PCB, together with its mounted components can be organised into a primary and secondary sector. As it is shown in the Figure 9, the primary side is connected to the input wires and contains (Torres, 2006):

- one or two large electrolytic capacitors, depending on the type of PSU,
- an aluminium heatsink, also called a passive aluminium cooler,
- transient filtering, and
- an active or passive Power Factor Correction (PFC).

The first phase of SMPS is the transient filtering. In terms of weight, the most significant components are ferrite coils. Depending on the model, transient filtering phase contains none, one, or two ferrite coils. The ferrite coils have a Ni-Zn ceramic ring-shaped core, which is enveloped by conducting wire. The conducting wire is predominantly made of Cu (Mahyum, 2012). The Transient filtering phase includes also two polyester capacitors (X series) and two ceramic disc capacitors (Y series). Y series capacitors are usually coloured in blue. Technologically, the most important component is a Metal Oxide Varistor, in the literature referred also as MOV or varistor. The MOV is a voltage dependent, nonlinear device and its function is to absorb destructive energy surplus and dissipate it as heat. In terms of material composition, a core of MOV is made of zinc oxide grains in a matrix of other metal oxides, e.g. Bi, Co, Mn. The core is enveloped by two metal electrodes. The MOV is usually coloured in yellow (Marian, 2010).

According to Torres (2006), active PFC usually consists of two power metal–oxide–semiconductor field-effect transistors (MOSFET). Both transistors are attached to a passive aluminium heatsink on the primary side. Unlike PFC diode, which is also attached to the passive aluminium heatsink, the transistors have three terminals, i.e. source, drain, and gate. The active PFC transistors are used in order to improve the ratio between the useful (true) power (kW) and the total power (kVA) (Ware, 2006, Torres, 2008). Some models may contain separate passive aluminium heatsink for the PFC.

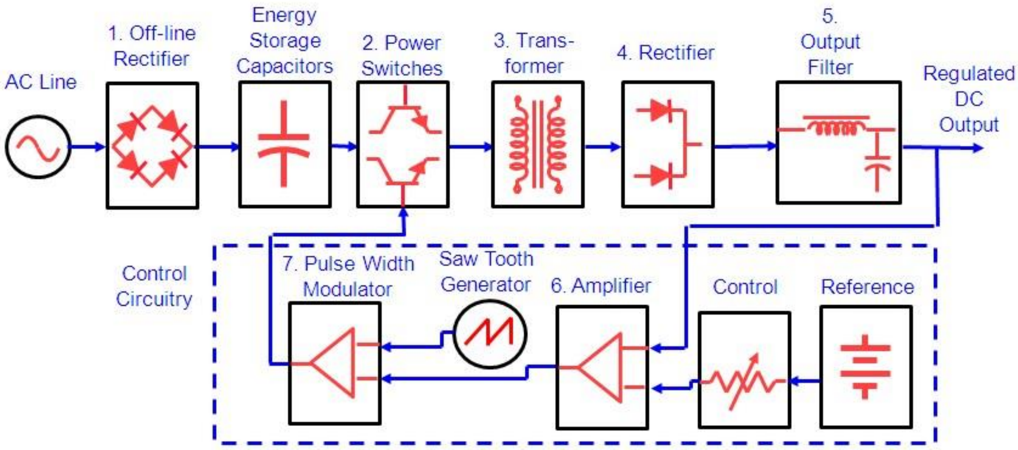


Figure 8: Block diagram of SMPS (Brorein, 2011)

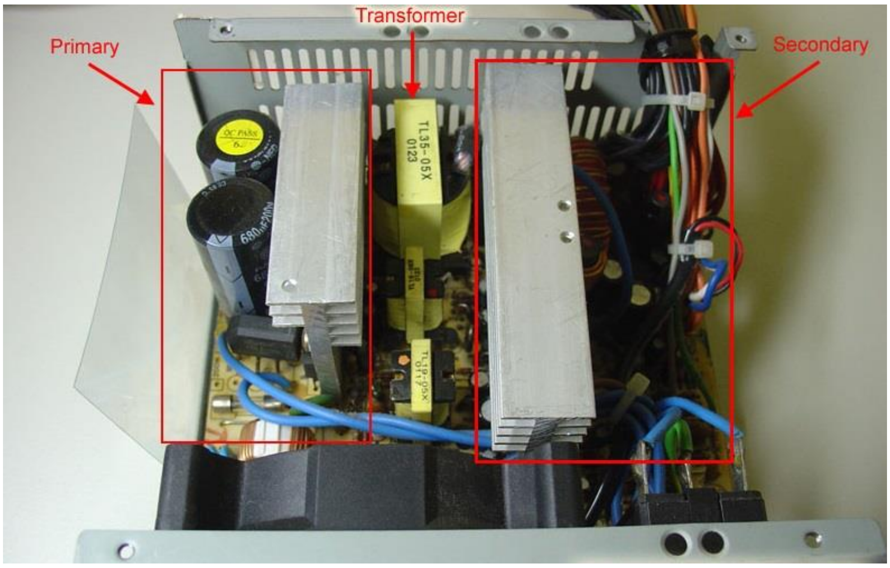


Figure 9: Structure of PSU from PC (Torres, 2006)

The SMPS contains either one or two large aluminium electrolytic capacitors. If the model contains an active PFC, then there will be only one electrolytic capacitor, whereas a passive PFC, requires two electrolytic capacitors (Torres, 2006). The electrolytic capacitor is essentially a piece of paper soaked in an electrolyte fluid and placed between two pieces of aluminium foil. The anode of the electrolytic capacitor is made of a 20-100 µm thick aluminium foil of at least 99.99% purity. The Cathode foil is made of aluminium with the 99.8% purity but contains Cu, Ti, or Si in traces in order to prevent the oxidation during the discharge (Sparkfun, 2013). Both cathode and anode foils are etched to increase the specific surface area. The capacitor is encapsulated in the aluminium housing in order to circumvent galvanization. A sealing material depends on the model of the capacitor, varying between plastic and phenolic laminated resin (Ord, 1991, Sparkfun, 2013).

As it is mentioned above, the SMPS has usually three transformers. The main transformer is also the largest one and its primary coil is connected to the switching transistors and its secondary coil with the rectifying diodes and filtering circuits that provide the PC with DC. The second transformer's function is to provide +5VSB output and the third transformer is an isolator transformer (Torres, 2006). All three transformers are shell type transformers with a laminated core. The core is made of electrical steel and windings are a conductive wire, made predominantly of copper (McLyman, 2004).

An electrical current from the transformers passes through rectifying and filtering operations and it is subsequently distributed to the other components of a PC by output wires. The rectifying and filtering operations are part of the secondary sector, which includes several smaller electrolytic capacitors, ferrite coils, and several solid-state diodes and Schottky diodes (or rectifiers) in order to filter and rectify the DC output to the PC (Ware, 2006, Torres, 2006). According to Torres (2006), the rectifiers are mounted on the secondary passive aluminium heatsink and are visually similar to the transistors from the primary sector, but unlike transistors, they contain two power diodes each. The rectification of the negative voltages, i.e. -5 V, and -12 V, is carried out by the solid-state diodes, whereas the rectification of the positive voltage, i.e. +3.3 V, +5 V, and +12 V, is carried out by the power Schottky diodes.

There are several types of connectors for power distribution from the SMPS to the other PC components (Torres, 2008):

- Main motherboard connector – is one of the cable that connects SMPS and motherboard. It uses either 24-pin or 20-pin connectors and it is designated as ATX12V 2.x, ATX12V 1.x, or ATX motherboard;
- ATX12V connector – connects the SMPS and a CPU and uses a 4-pin connector;
- EPS12V connector – it has the same function as ATX12V, but it has 8-pin connector and therefore is capable to supply the CPU with more power;
- Motherboard 6-pin auxiliary power connector – is a type of connector that is not in use anymore. It has 6-pin connector;
- Motherboard 12-pin connector – is also a type of connector that is not in use anymore. It became obsolete when an ATX standard was introduced. The motherboard connector used two 6-pin connectors.

The PSUs are generally classified according to the maximum power they can provide. However, this classification can also be a cause for confusion, since different manufacturers define the power output of the PSU differently. It is defined either as a peak wattage, which can last for a brief moment, measured maximum power output with an unrealistic room temperature, or simply falsely stated (Torres, 2008).

2.1.4 Active fans from PC

The active fan (also called a cooler) carries out a significant role in maintaining an optimal temperature inside PSU and consequently a temperature of a whole PC. As the computing technology is advancing, so is the temperature within the PC case. The sources of heat in a system are processor, graphics processing unit (GPU), voltage regulator modules (VRM), chipset, and a high-performance RAM (Kikugawa, 2015, Torres, 2008).

As it is stated by Kikugawa (2015), the increased temperature has can have negative effects on the PC, such as wear and decreased reliability of the components, and induces a thermal stress. The reliability of components influences how stable is a component at a given performance level. The effects of the thermal stress are a repetitive thermally induced expansion and subsequent contraction caused by cooling. These heating and cooling cycles cause a mechanical stress to the component and lead to the accelerated wear of a material which can lead to cracks and breaks of the material. The negative effects of the thermal stress are more evident, as the absolute difference between temperature extremes is higher.

There are several different cooling options currently available subdivided between two major cooling principles: air cooling and liquid cooling. The air cooling consists of a heatsink (passive aluminium heatsink), heat pipes, and the active fan (Kikugawa, 2015). However, in this chapter, only the active fan will be considered.

The primary function of the active fan is to maintain airflow within the PC case. However, the larger case offers also more airflow and fewer interferences. Depending on the size on the design of the PC case and the number of installed active fans, there are two major airflow configurations: negative pressure and positive pressure airflow.

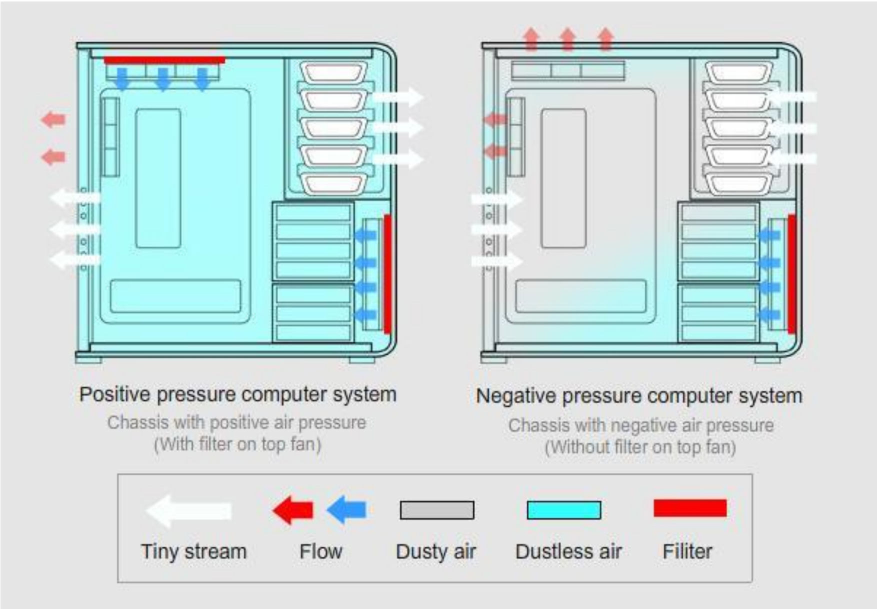


Figure 10: Overview of airflow configurations (SilverStone, 2008)

The negative pressure airflow means that more air is being exhausted than inflated. The underlying idea is to exhaust the hot air as promptly and to allow the cooler air to be sucked in by the negative pressure within the PC case. However, this configuration has two major disadvantages. One is that besides the cooler air also dust is being sucked in by negative pressure. The other disadvantage is that the exhaust air might be sucked back in the case (Kikugawa, 2015). The positive pressure relies on a principle that more air is being blown in the PC case than exhausted. This configuration blows in less dust than the negative pressure configuration and also reduces the risk of recirculating the hot air (SilverStone, 2008). A comparison of the two configurations is shown in Figure 10.

In general, there are two sizes of the active fan in use, the 80 mm active fan and the 120 mm active fan. The larger active fan produces the higher airflow and a lower noise level since even lower rotations speed can induce same or higher airflow as the smaller active fan (Torres, 2008). According to SilverStone (2008), as silent active fans can be considered these, which produce the noise below 40 dB. However, if the noise level supersedes 50 dB, can already considered as loud.

2.1.5 Power Supply Units for Printers

Power Supply Units for printers is a linear type of PSU. Although not completely the same, based on the similar principle, many other PSU for printers are also alternatively known as an AC/DC adapter, AC adapter, or AC converter. The conversion process of linear PSUs is very similar to the SMPS described in detail in the chapter 2.1.3. Namely, the linear PSU contains a transformer, which converts a voltage from the power grid to a lower voltage. Furthermore, power Schottky diodes (also called a rectifier) are converting AC into pulsating DC. Finally, filters are used to smooth the pulsating waveform to a neglectable level. The required power output determines the size of the transformer, which is a single largest component and thus by influences the significantly the total size of the PSU (Calwell and Reeder, 2002).

The linear PSU can be designed to be compatible with several different devices simultaneously, e.g. to have an output range between 100 to 240 V or 70 to 125 W and to have multiple types and sizes of connectors (ComputerHope, 2017). This kind of linear PSUs are also called universal adapters.

The linear PSU has several distinctive favourable characteristics. First, by placing the PSU outside of the device, there is a significant saving in size and weight and there by increases the mobility of the device. Also, the external PSU can be repaired or replaced without opening the device. This characteristic is of special importance since the PSU is sensitive to the power peaks and heat generation. Furthermore, by separating the PSU outside and the device, it is possible to reduce the generation of excessive heat generation in the device itself. Finally, the production costs of linear PSU are significantly lower than of the SMPS (HDP, 2017).

However, the linear PSU also have several disadvantages compared to the SMPS. For example, if the linear PSU are used in high power purposes, they require a large transformer and large other components in order to deal with the high power. The larger transformer leads subsequently to the increase of the overall size and weight and poses a challenge for weight distribution (HDP, 2017). Furthermore, the linear PSU have significantly lower efficiency compared to the SMPS, especially if there is a large difference between input and output voltage. Also, some power is still being wasted even when the PSU is left running and the device power is switched off or the device has been disconnected from the PSU (Calwell and Reeder, 2002). Finally, up to this point, the PSU connector has not been standardized, which causes much confusion and damage to the equipment by improper use.

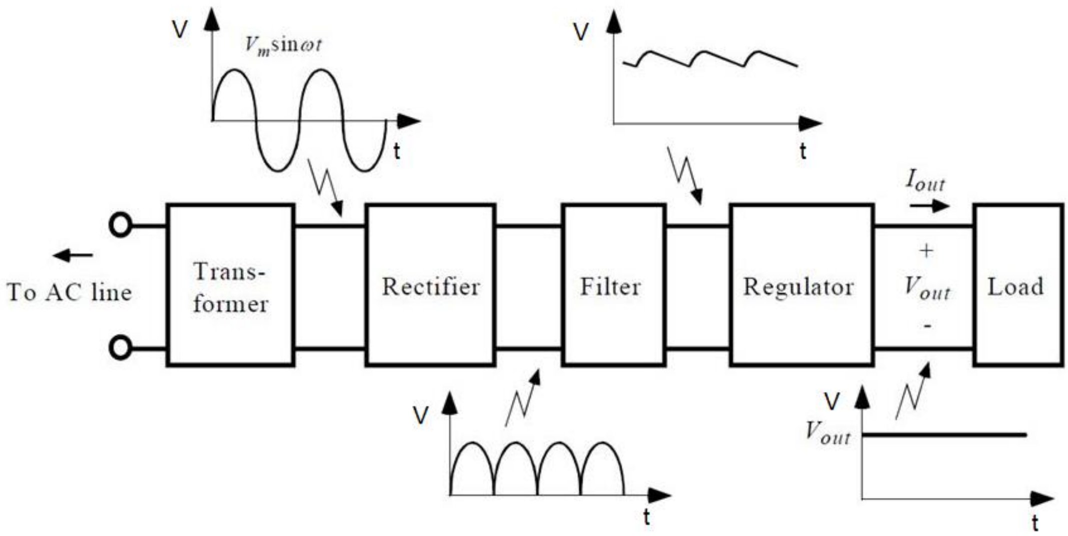


Figure 11: Block diagram of linear PSU (Byfield, 2015)

2.2 In-depth manual disassembly

In-depth manual disassembly is a simple method requiring only the basic tools for a successful analysis. The success is correlated with a possibility to determine the material composition of resulting parts after the analysis. The aim of the analysis is to disassemble and separate target components into single materials, so that they can be identified and allocated to homogenous material groups, e.g. plastics, copper, ferrous metals, etc. The complex components that are included within the scope of this master's theses, were first disassembled into component parts and thereupon obtained parts were further separated or broken apart mechanically so that a share of material assemblies (material composites) was kept as low as possible. Finally, the obtained materials were identified according to their function, colour, density, magnetic properties and similar.

A set of tools used for disassembling and separation of the complex components included an assortment of screwdrivers, large hammer, a set of locking pliers, cutting pliers, metal files, and a heavy table vice clamp. Particularly important for the disassembly procedure is the screwdriver assortment comprising of a set of interchangeable star bits, since the complex components in the EEE are kept together with a variety of different screw sizes (and shapes). Moreover, large flat-blade screwdrivers are used in combination with a hammer to separate moulded or glued electronic components from a casing or from other electronic elements.

After the complex components have been disassembled, the resulting parts have been organised and labelled on the working surface and analysed by simple material identification analysis (see chapter 2.3). The resulting parts are organised into two interconnected levels. The first level is constituted from parts structured according to their functions, e.g. casing, screws, PCB, and the second level is structured according to the materials they are made of. Whenever it is possible, the functioning parts are disassembled into single homogenous materials. By following this procedure, it is possible to accurately locate the potential changes in material composition between models of complex components or to track the change in the material composition over the years.

Furthermore, this method of analysis makes possible enhancement of the results for the components, whose precise material identification exceeds the scope of the research, e.g. PCBs, magnets, platters from HDDs, and similar, with data from literature notably uncomplicated

2.2.1 Hard Disk Drives

An in-depth disassembly and analysis of over 30 different 3,5” Hard Disk Drives (HDDs) from desktop computers randomly collected from the local waste stream. Prior to the dismantling procedure, basic information, e.g. year of production and storage capacity, has been acquired by checking each model at the respective producer homepage. An overview of analysed HDDs is shown in Table 1.

Figure 12: Example of disassembled HDD with labelled parts

Table 1: Hard-Disk Drive sample set for in-depth analysis

Model-ID	Weight [g]	Year of manufacture	Manufacturer	Model	Model-ID	Capacity [GB]
HD-1	498.4	1997	Seagate	Tonka IDR	M255	6.4
HD-2	584.7	2002	Seagate	Tonka R	M87	40
HD-3	581.5	2002	Maxtor	DiamondMax	Plus 9	120
HD-4	586.4	2011	Seagate	Barracuda	7200	320
HD-5	582	2008	Western Digital		WD2500JB - 00REA0	250
HD-6	479.7	1997	Maxtor	N257	84320D4	4.3
HD-8	663.3	2007	Hitachi	Deskstar	HDS721075KLA330	750
HD-9	570.1	2000	Seagate	U10	ST310212A	10.2
HD-10	679.6	1996	Seagate			0.5
HD-11	578.8	2006	Western Digital		WD3200JB - 00KFA0	320
HD-12	557.7	2003	Seagate	Barracuda	7200.7	160
HD-13	622.3	2007	Seagate	Barracuda	7200.11	640
HD-14	615	2002	Western Digital		WD2000JB - 00GVA0	200
HD-15	535.2	2004	Seagate	Barracuda	7200.7	40
HD-16	607.1	2004	Western Digital		WD300JB - 00KFA0	300
HD-17	623	2005	Maxtor			250
HD-18	568.8	2003	Seagate	Barracuda	7200.7	120
HD-19	612.8	2005	Samsung		SP0812N	80
HD-20	580.2	2006	Hitachi		0A31611BA1	250
HD-21	594.4	2005	Seagate		ST3250823AS	250
HD-22	569.3	2003	Seagate		ST3160022A	160
HD-23	475.7	2010	Samsung		HD503HI	500
HD-24	576.7	2001	Quantum	Fireball	Plus AS	20,5
HD-25	516.3	2002	Maxtor	DiamondMax	Plus 9	80
HD-26	416.9	2008	Hitachi	Deskstar	HDP725016GLA380	160
HD-27	569.3	2003	Seagate	Barracuda	7200.7	160
HD-28	458.3	2007	Western Digital		WD800JD	80
HD-29	554.2	2003	Hitachi	Deskstar	IC35L060AVV207-0	61.4
HD-30	419	2009	Hitachi	Deskstar	HDP725016GLA380	160
HD-31	544	2006	Hitachi	Deskstar	HDS728040PLA320	40
HD-32	565.6	2003	Seagate	Barracuda	7200.7	160

The components and parts resulting from the in-depth disassembly have been then organised, designated, and photographed on a working surface. In order to make a comparison between the components and parts from different comparable HDDs, all components and parts have been designated with the same numbers and organised on the working surface in the similar order. An example of disassembled HDD is shown in Figure 12.

DC spindle motor assembly, actuator arm, and magnets from a voice coil assembly require particular attention in order to achieve complete disassembly. In the literature, the prevailing method for in-depth disassembly of these components requires using a gas torch for achieving the temperatures above 2000 °C. Direct current (DC) spindle motor assembly and actuator arm are disjointed based on different coefficients of thermal expansion of constituting metals, and magnets from the voice coil assembly are detached from the retainers by reaching the Curie temperature and thus destroying the magnetic properties of the magnets (München and Veit, 2017, Ueberschaar and Rotter, 2015). However, in this research only mechanical force is used to disjoin these components. The DC spindle motor assembly and actuator arm are disjointed using a very large screwdriver and a hammer, and magnets are liberated by twisting the ferrous retainers with a set of large pliers.

After the in-depth disassembly, the parts have been analysed for materials following the simple analytical procedure described in the chapter 2.3. Identified parts have been then weighed and attributed according to the used material classification and to a functional classification.

2.2.2 Optical Disc Drives

Within the scope of the research, 15 Optical Disc Drives (ODD) were analysed via in-depth dismantling analysis. Prior to the in-depth dismantling, all available information about the ODDs, e.g. model, year of manufacture, etc., have been recorded and confirmed by verifying it at the respective producer homepage. A complete list of analysed ODDs is presented in Table 2.

The parts resulting from the in-depth disassembly have been organised on the working surface. Each part has been labelled with the same number in order to enable better comparability of different ODD models. Subsequently, each part has been analysed by simple material identification analysis (chapter 2.3) and attributed to a specific function it was performing before the ODD became obsolete. An overview of a completely disassembled ODD is shown in Figure 13.

In terms of material composition, the most complex part of ODD is the laser assembly (part no. 26 in Figure 13). Based on the current recycling practice in Europe, it assumed that the optical sensor as part of the ODD does not contain a particularly high concentration of precious metals or REE. Thus, due to high complexity and relatively low recycling potential, the laser assemblies have not been further disassembled within the scope of this research.

Figure 13: Example of disassembled Optical Disc Drive with labelled parts

Table 2: ODD sample set for in-depth analysis

Model No.	Model-ID	Year of manufacture	Weight [g]	Manufacturer	Model
1	CD-ROM-01	N/A	723.5	N/A	N/A
2	CD-ROM-02	N/A	954	N/A	N/A
3	CD-ROM-04	N/A	733	N/A	N/A
4	CD-ROM-06	N/A	983.8	N/A	N/A
7	CD-ROM-10	1995	897.8	Sanyo Electric Co., Ltd.	CRD - 254P (GR)
8	CD-ROM-11	1996	822.4	Mitsumi	CRMC-FX400E
9	CD-ROM-12	2000	939.8	Mitsumi	CRMC-FX4830T
10	CD-ROM-13	2002	782	LG	DRD-8160B
11	CD-ROM-14	2003	892	Toshiba	SD-M1802
12	CD-ROM-15	2005	669.2	LG	GCC-4482B
5	CD-ROM-07	2006	1147.1	Sony	DW-G121A
6	CD-ROM-09	2006	742.8	LG	GSA - 4167B
13	CD-ROM-16	2007	677.2	LG	GH20NS10
14	CD-ROM-17	2007	741.3	LG	GSA - H30L
15	CD-ROM-18	2008	683.7	Philips	DH-20A4P

2.2.3 Power Supply Unit from PCs

A total of 10 different Power Supply Units (PSU) from PC have been analysed via in-depth dismantling analysis. Similarly, as it was the case with HDDs and ODDs, all available information about the components have been recorded. Active fans from PSUs have been sorted out and analysed as a separate subgroup of complex components. An overview of a completely disassembled PSU (PC) is shown in Figure 14.

The parts resulting from the in-depth dismantling have been organised and labelled following the same principle as it was the case with HDDs and PSUs and thus enabling a better comparison between different models. Within the scope of this research, the only component dismantled from the PCB and analysed separately was aluminium passive heatsink (parts labelled with no. 10 and no. 11 in Figure 14). A large transformer, labelled as no. 19, were in the most cases not mounted on the PCB and therefore weighted and documented separately from the PCB. A complete overview of analysed PSU-PCs are shown in Table 3.

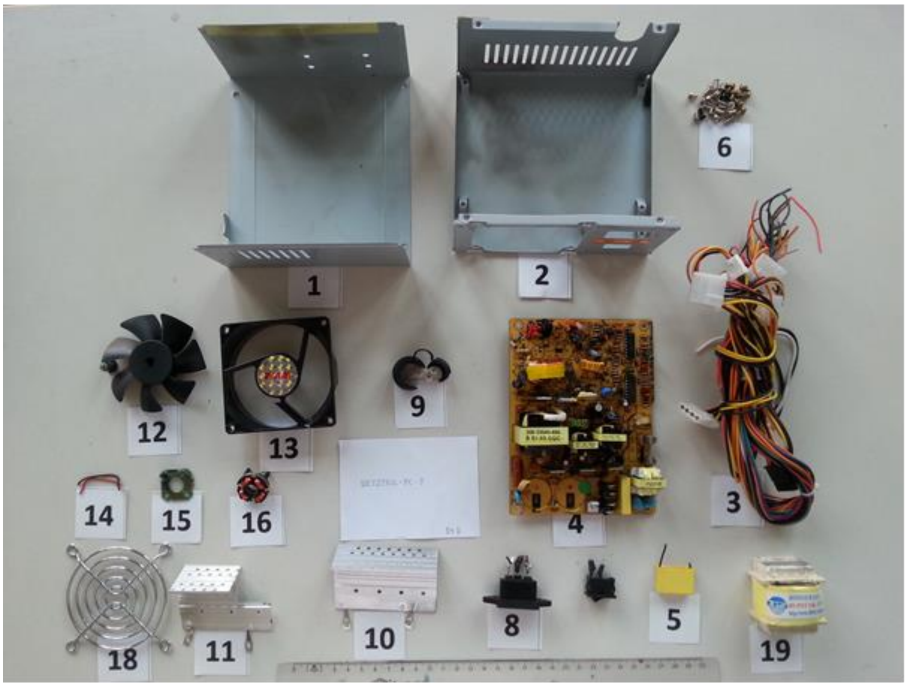


Figure 14: Example of disassembled PSU (PC) with labelled parts

Table 3: Power Supply Unit-PC sample set for in-depth analysis

Model No.	Model-ID	Year of manufacture	Component type	Weight [g]	Manufacturer	Model
1	Netzteil-PC-1	2005	Power Supply Unit - PC	1428.3	Vikings	MPT-350
2	Netzteil-PC-2	1998	Power Supply Unit - PC	1913.95	NanoPoint	SP-350P1B
3	Netzteil-PC-3	1997	Power Supply Unit - PC	1967.1	N/E	N/E
4	Netzteil-PC-4	1997	Power Supply Unit - PC	1044.55	JNC Computer Crop.	LC-235ATX
5	Netzteil-PC-5	2004	Power Supply Unit - PC	1729.1	Delta Electronics	GPS-300AB-100L
6	Netzteil-PC-6	2000	Power Supply Unit - PC	1284.25	PC WINNER	ST-300ATX
7	Netzteil-PC-7	2004	Power Supply Unit - PC	1174.1	Cemos	CP4-350WS
8	Netzteil-PC-8	2001	Power Supply Unit - PC	1060.5	JNC Computer Crop.	LC-A350ATX
9	Netzteil-PC-9	2007	Power Supply Unit - PC	1145.65	Rasurgo	RBP-450CL
10	Netzteil-PC-10	2005	Power Supply Unit - PC	1855.75	Bestec	ATX-300-12Z

2.2.4 Fans from PC Power Supply Unit

Active cooling units (plastic fans) originating from PC Power Supply Units have been analysed via in-depth disassembly method. Due to their material complexity and since they are also found in other devices too, the active fans have been regarded as separate complex components. Within the scope of the in-depth disassembly, 11 fans have been analysed. These fans have been dismounted from already analysed PSU-PC so that also the year of manufacture can also be tracked.

Similarly, as it was the case with other complex components, the fans have been disassembled and broken apart to its basic constituents until the resulting parts were made from as homogenous as possible materials. Structural parts include following: plastic casing, plastic propeller, a very small and simple PCB, copper coil, short wires, permanent magnet and its ferrous metal casing, and the core of the electric motor made of copper and ferrous iron. A detailed overview of disassembled fans is available in Table 4.

Table 4: Fan sample set for in-depth analysis

Model No.	Model-ID	From	Weight [g]	Year of manufacture
1	Fan-PC-1	Netzteil-PC-1	67.5	2005
2	Fan-PC-2	Netzteil-PC-2	57.0	1998
3	Fan-PC-3	Netzteil-PC-2	57.2	1998
4	Fan-PC-4	Netzteil-PC-3	120.8	1997
5	Fan-PC-5	Netzteil-PC-4	57.5	1997
6	Fan-PC-6	Netzteil-PC-5	69.3	2004
7	Fan-PC-7	Netzteil-PC-6	72.5	2000
8	Fan-PC-8	Netzteil-PC-7	46.9	2004
9	Fan-PC-9	Netzteil-PC-8	71.9	2001
10	Fan-PC-10	Netzteil-PC-9	56.5	2007
11	Fan-PC-11	Netzteil-PC-10	64.6	2005

2.2.5 Power Supply Unit for printers

Within the scope of the research, 10 Power Supply Units from printers (PSU-Printers) were randomly collected from the local recycling company and analysed via in-depth dismantling analysis. Prior to the in-depth dismantling, all available information about the PSU-Printers, e.g. model, production year, etc., have been tracked and confirmed by the information set available by the respective manufacturer. An example of dismantled PSU-Printer is shown in Figure 15.

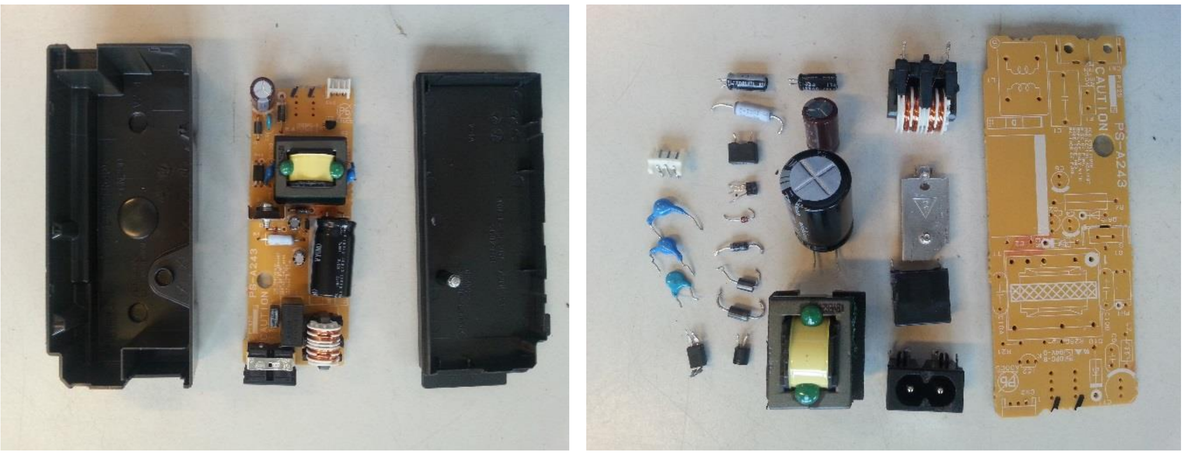


Figure 15: Example of disassembled PSU-Printer

PSU-Printers have a fairly simple structure including casing, PCB, and usually only one screw holding the casing together. Within the scope of this research, the cables were not considered as part of the PSU-Printers and were, therefore, cut off before weighting. A complete overview of analysed PSU-Printers is available in Table 5.

Table 5: Power Supply Unit-Printers sample set for in-depth analysis

Model No.	Model-ID	Device	Weight [g]	Manufacturer	Model
1	Netzteil-1	Power Supply Unit - Printer	178.0	Canon	K30290
2	Netzteil-2	Power Supply Unit - Printer	134.0	Canon	K30329
3	Netzteil-3	Power Supply Unit - Printer	321.0	Canon	K30253
4	Netzteil-4	Power Supply Unit - Printer	235.0	Canon	K30246
5	Netzteil-5	Power Supply Unit - Printer	146.0	Canon	K30314
6	Netzteil-6	Power Supply Unit - Printer	122.0	N/E	1A541W
7	Netzteil-7	Power Supply Unit - Printer	210.0	Canon	K30344
8	Netzteil-8	Power Supply Unit - Printer	147.0	Canon	K30304
9	Netzteil-9	Power Supply Unit - Printer	149.0	Canon	K30314
10	Netzteil-10	Power Supply Unit - Printer	118.0	N/E	LMK-U15A

2.3 Simple material identification analysis

After the complex components have been separated according to the materials they are made of, the procedure of identification of specific metals can be initiated. The classification and identification of materials begin with the general categorisation between metals and plastics. Since analysis of the plastics is not in the focus of this research, these materials will not be further analysed. The metal fraction is subdivided into “coloured” metals “grey” metals. The coloured metals make a quantitatively smaller group and they are generally identified by the specific function of a component they are forming, e.g. wires, electronic connectors (so-called “gold fingers”), etc. The metal file can be used to examine if the metal piece in focus is coloured or if is coated (e.g. galvanised). Any further analysis would require more advanced analytical methods.

The grey metals are first tested for their magnetic properties. The magnetic fraction is constituted either from ferrous metals or nickel. The following tests have been developed based on the information and suggestions from Dulski (1996).

The **magnet test** is used to set apart magnetic from non-magnetic grey metals. The magnetic fractions include ferrous metals, nickel, and ferrite. It is fairly simple, but important to segregate the ferrite from the other metals since the ferrite is actually a ceramic compound made of iron oxide ($Fe2O3$). Ferrites are usually used to as a core of different types of transformers or as permanent magnets.

The **nickel test** is used to set apart ferrous and nickel fractions. Since both metals are magnetic and have similar density additional test needs to be applied to set them apart. For this purpose, one drop of 10% ammonia followed by one drop of dimethylglyoxime are dripped on a cotton bud. The cotton bud is thereafter rubbed for 15-20 sec. against the surface of the metal in focus. If the cotton bud turns pink or red, then the metal is nickel. If the cotton bud does not change colour, then it is a ferrous metal fraction.

The **swim/sink test** is performed in order to differentiate the non-magnetic fractions. For this purpose, a sodium polytungstate solution with a density of 3,1 g/cm3 was used. Aluminium and magnesium metal pieces, whose density does not exceed 2,8 g/cm3, will float on the surface of the solution. However, the lead, which as the density of 10,6 g/cm3, will sink rapidly to the bottom of the container with the sodium polytungstate solution. This test will show satisfactory results as long as the pieces are not too small, in which case, it can happen that the surface tension of the solution would prevent a denser metal from sinking and thus the test would provide inadequate results.

The **acid test** is performed in order to differentiate the magnesium aluminium fractions. Although, the magnesium has the density of 1,7 g/cm3, which is app. two thirds of the density of aluminium (2,5-2,8 g/cm3), a more practical test is needed in order to differentiate these two metals. For this purpose, a very simple test using apple cider vinegar was conducted – few droplets of vinegar are dripped directly on the surface of the metal in focus. The magnesium will almost instantaneously start reacting with the vinegar. Unlike magnesium, the aluminium will stay inert and there will not be any visible signs of a reaction. Instead of vinegar, any other corrosive acid could have been used in its place.

Alternatively, to the acid test, there is another simple test in order to differentiate between magnesium and aluminium. Using a metal file a fraction of material is trimmed from the sample and then the trimmed material is to set on fire with a match. If the metal in focus is magnesium, then it will burn since magnesium is flammable. Then again, the aluminium will not burn, since it is not flammable.

A full overview and the procedure of the dismantled and homogenized samples can be observed in Figure 16.

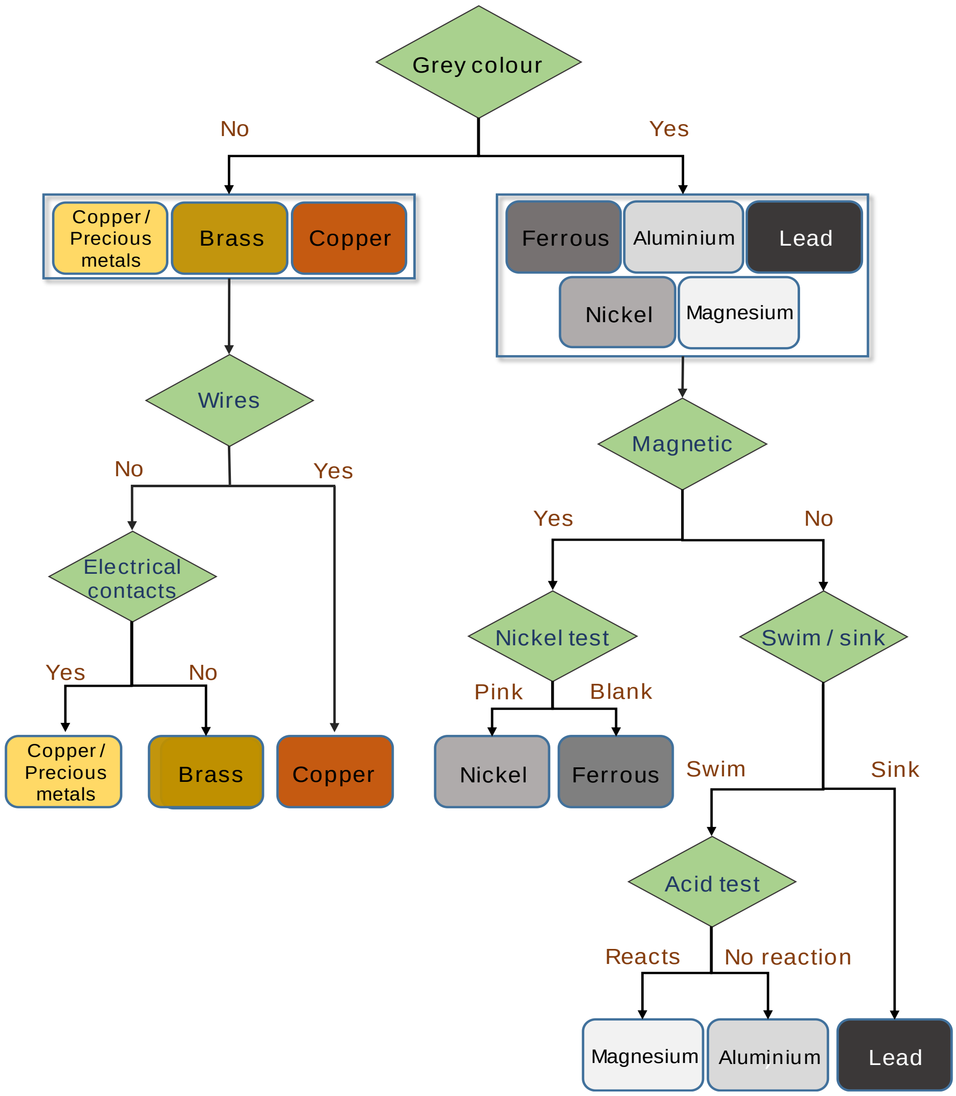


Figure 16: Structure of manual separation analysis

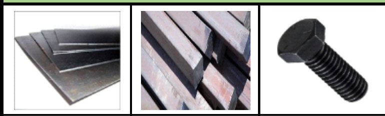
For better identification and classification of metals contained in the complex components, a material catalogue was developed. The catalogue contains 10 different metals and alloys that could be identified by manual separation analysis. The catalogue contains basic characteristics of the metals and alloys, e.g. colour, density, magnetic properties, typical use and similar.

These metals and alloys are classified into three different subcategories based on their typical colour:

- Yellow/red: brass, bronze copper
- Shiny grey: chromium, nickel, stainless steel
- Dull grey: aluminium, mild steel (carbon steel), magnesium and lead

Not included in the catalogue, but significant for complex components, are gold, silver, and rare earth elements (REE), because they usually come in alloys with other base metals and/or are present in very small concentrations and thus they cannot be identified via manual separation analysis method. The full catalogue can be observed in Table 6.

Table 6: Material catalogue

Yellow → Red		
Brass	**Bronze**	**Copper**
		
Alloy of Cu + Zn	Alloy of Cu + Sn (app. 12%)	Light red colour
Yellow / gold colour	Yellow; darker if oxidized	Gets green(-ish) over time
Non-ferrous	Non-ferrous	Non-ferrous
Density between 8,4-8,7 g/cm3	Density between 7,4-8,9 g/cm3	Density between 8,96 g/cm3
Used there where simultaneously el. conductivity and mech. stability is needed	Used where combination of toughness and resistance to salt water corrosion is needed	Used where good electrical conductivity is needed (e.g. wires)
Source (photos): pinterest.com; w orldpress.com; http://blog.krrb.com/	Source (photos): squareup.com; pinterest.com; mycomponents.co.uk	Source (photos): colorcopper.com; dir.indiamart.com;
Shiny grey		
Chromium	**Nickel**	**Steinless steel**
		
Very shini silver colour	Shiny when polished	Shiny silver colour
Non-ferrous	Darker gray when unpolished	Does not form an oxide
Used for coating	Non-ferrous	Ferrous
Resistant to corrosion and temperature	Magnetic	Non-magnetic, except 4XX series
Density 7,2 g/cm3	Density 8,9 g/cm3	Density 7,4-8 g/cm3
Source (photos): bbc.com; teachnuclear.ca; indiamart.com	Source (photos): commons.w ikimedia.org; dir.indiamart.com; fleur-de-coin.com	Source (photos): ezfauxdecor.com; specifile.co.za; prochem.cloudsites.net
Dull grey		
Aluminium	**Mild stell - carbon steel**	**Lead**
		
Soft, ductile, corrosion resistant	Darker colour than stainless steel	Dull grey when unpolished
High electrical conductivity	Carbon content 0,12 - 2 wt.%	Shinier when polished
Non-ferrous	Corrosive	Non-Ferrous
Very light	Magnetic	Very heavy
Density 2,5 -2,8 g/cm3	Density app. 7,85 g/cm3	Density 10,6 g/cm3
Source (photos): w ikimedia.org; images.naldzgraphics.net; amazon.com	Source (photos): continentalsteel.com; onealsteel.com; http://4.imimg.com/	Source (photos): nw -roofing.co.uk; southindiametal.com; http://i.stack.imgur.com/
Dull grey		
Magnesium		
		
Silvery-white colour		
Flammable		
Non-ferrous		
Very light		
Density 1,7 g/cm3		
Source: dsmag.co.il; lifeartschool.co.za; http://fastermold.com/		

2.4 Inductively Coupled Plasma – Optic Emission Spectroscopy

The aim of an Inductively Coupled Plasma – Optic Emission Spectroscopy (ICP-OES) analysis was to determine the metal composition of aluminium capacitors with non-solid electrolyte originating from motherboard Printed Circuit Boards (PCB) from personal computers (PC). Since the main metal constituent of the aluminium capacitor is aluminium (Cousseau et al., 2017) and can be identified by simple analytical procedure described in Chapter 2.3, the focus of the ICP-OES analysis were following objectives:

- Identification of trace metals in aluminium capacitors and, if possible, the determination of their quantity per sample
- Comparison of applied digestion methods with regards to the dissolution efficiency of metals

2.4.1 Apparatus and instruments

Preparation and acid digestion of the samples was carried out in a clean laboratory. Ultra High Purity water (UHP), produced on site at the laboratory, was used for all the dilutions. An overhead tube rotator (Lab Companion CRT-350 Rotator) was used to increase the exposure of the samples to the digesting acid. It has a capacity for 12 50 mL plastic tube reaction vessels. The rotator is operated at the room temperature (25° C) and has rotation speed range between 5-30 rpm.

SC100 HotBlock digester was applied for both nitric and aqua regia extraction of the samples. The digester has a capacity of 36 positions for 50 mL digestion tubes. It was operated at an average temperature of 80° C in a fume hood.

Thermo Scientific iCAP 6000 Series ICP-OES with ASX 520 auto sampler was used for the metal composition analysis of the aluminium capacitors. The wave length coverage of the spectrometer is 166-847 nm. Each of the analysed metals was measured at four different wave lengths. Furthermore, at least two different analyses were conducted with every sample – with two different reference material solutions.

C-601 Cress laboratory furnace with a temperature range from 109 – 1090° C was used for analysis of the acid extraction residues in order to confirm the metal digestion.

2.4.2 Mechanical preparation of the samples and construction of sample sets

The target samples were aluminium capacitors originating from “motherboard” type of Printed Circuit Boards (PCB), which were obtained in “DRZ” Vienna, Austria. After examining 40 different motherboard PCBs manufactured in the time frame from 1991-2010, it could have been concluded that the aluminium capacitors can generally be classified into three different subgroups according to their size (the length of the longest edge):

1. < 15 mm,
2. 15-25 mm, and
3. > 25 mm

The ICP equipment is very sensitive and usually, sample intake is very small, in general, 0.1 g of solid samplee (cf. Abegaz, 2005). Therefore, for the practicality reasons was first subgroup < 15 mm chosen as the focus type of aluminium capacitors, which will be analysed by the ICP-OES.

The chosen first subgroup < 15 mm capacitors were then taken from motherboard PCBs. The detachment was carried out with a soldering gun and a flat-blade screwdriver in order to keep the connectors from detaching from the capacitor. The detached capacitors were then organised into two sample sets. Each sample set contained five capacitors originating from different motherboard PCBs. Table 7 shows a list of the taken samples.

Table 7: Overview of the samples and their classification into sample sets

Sample set 1 [2004]		**Sample set 2 [2004]**	
Sample number	Weight [g]	Sample number	Weight [g]
1	0.5865	6	0.5154
2	0.5596	7	0.5616
3	0.5655	8	0.4950
4	0.4706	9	0.5610
5	0.5612	10	0.4650
Average	0.5487	Average	0.5196

After the capacitors have been detached from the PCBs, they needed to be reduced in size for a proper acid digestion. Within the scope of this research, the capacitors were simply cut in at least four pieces using pliers for cutting metal and subsequently brought to the acid digestion. Each sample included the whole capacitor and therefore, no sample replicas were created.

2.4.3 Digestion procedure

Up to the present moment, there are no readily available certified reference materials (CRM) with similar matrices as WEEE (cf. Strnad et al., 2016). A CRM has known concentrations of target materials, which are used for the calibration of an analytical instrument. For this reason, the analytical procedure was carried out with two CRMs, i.e. Fisher Chemical ME/1001/05 and TraceCERT 41135, which are usually used for analysis of soil sediments and together cover over 40 different metals. A detailed information about CRM is available in Table 8.

Table 8: Elements and matrices in applied CRM for ICP-OES analysis

CRM	Elements	Matrix
Fisher Chemical ME/1001/05 (CRM 1)	Al, Ag, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, and Zn	5% HNO3 0.1% C6H4O6
TraceCESRT 411 (CRM 2)	Au, Ge, Hf, Ir, Mo, Nb, Pd, Pt, Re, Rh, Ru, Sb, Sn, Ta, Ti, W, Zr	5% HCl, 1% HF, traces of HNO_3

Procedure 1

Capacitors from the Sample set 1 were digested by means of aqua regia. Each sample (an entire mechanically fragmented aluminium capacitor) was placed in a polyethylene 50 mL digestion vessel. In addition to the five samples, also a process blank (PB) sample was created. The digestion vessels containing the samples and PB were first filled with 2 mL of HNO3 and immediately after with 6 mL of HCl. Thereby was the aqua regia 3:1 ratio attained. The digestion vessels were covered (not tightened) with a cap and were placed in the overhead tube rotator for two hours. Subsequently, the samples were placed in the HotBlock heater at 80° C for 4 hours. The digestion vessels were then filtered through 45 µm FilterMate via on tube direct filtration. The samples were subsequently diluted to 50 mL with UHP water. The resulting solutions were transferred to a new set of polyethylene vessels and stored for ICP-OES analyses in the refrigerator at the 4° C. The filter cake was collected and merged together into a single sample, which is then further analysed separately.

Procedure 2

Capacitors from the Sample set 2 were digested only by means of nitric acid. Each sample (an entire mechanically fragmented aluminium capacitor) was placed in a polyethylene 50 mL digestion vessel and in addition to the samples, also a PB sample was created. Subsequently, 8 mL of HNO_3 was added to each digestion vessel (including PB sample). The digestion vessels were covered (not tightened) with a cap and left at the room temperature for two hours. Subsequently, the digestion vessels were placed into an overhead tube rotator for 45 min. at the speed of 10 rpm. Finally, the samples were placed in the HotBlock heater at 80° C for 4 hours. The digestion vessels were then filtered through 45 µm FilterMate via on tube direct filtration. The samples were subsequently diluted to 50 mL with UHP water. The resulting solutions were transferred to a new set of polyethylene vessels and stored for ICP-OES analyses in the refrigerator at the 4° C. The filter cake was collected and merged together into a single sample, which is then further analysed separately.

3. Results

3.1 Hard Disk Drives

Within the scope of this research over 30 HDDs were analysed. The analysed sample includes HDDs manufactured between the years 1996 and 2011. An average mass per HDD is 559 ± 61 g. Although there was a significant increase in the storage capacity of HDDs since the mid-1990s, the average weight of HDDs did not change significantly due to the similar increase in the data storing efficiency. In Figure 17, total weight and capacity of analysed HDDs have been depicted with respect to the year of manufacture. Additionally, linear trend lines have been calculated for both weight and capacity. The storage capacity trend line confirms the expected increase in storage capacity over time. The results for capacity are significant at the 95% level. The trend line for the total weight per HDD are not significant at the 95% significance level, so the trend could not be confirmed.

The HDD casing is made of two parts: base part and the cover. In all analysed samples, the base was made of cast aluminium and weighs 246 ± 23 g. However, 10/31 analysed HDDs had also the cover made of aluminium and the other 22/31 HDDs had the cover made of ferrous metal. The cover has a mass of 113 ± 28 g. The casing makes more than 70 wt.% of the total HDD and as such has a significant influence on the total weight of HDD. However, by observing the whole sample neither increasing nor decreasing trend in weight could have been determined for HDD casing. An overview and weight of structural parts constituting analysed HDDs is shown in Figure 18.

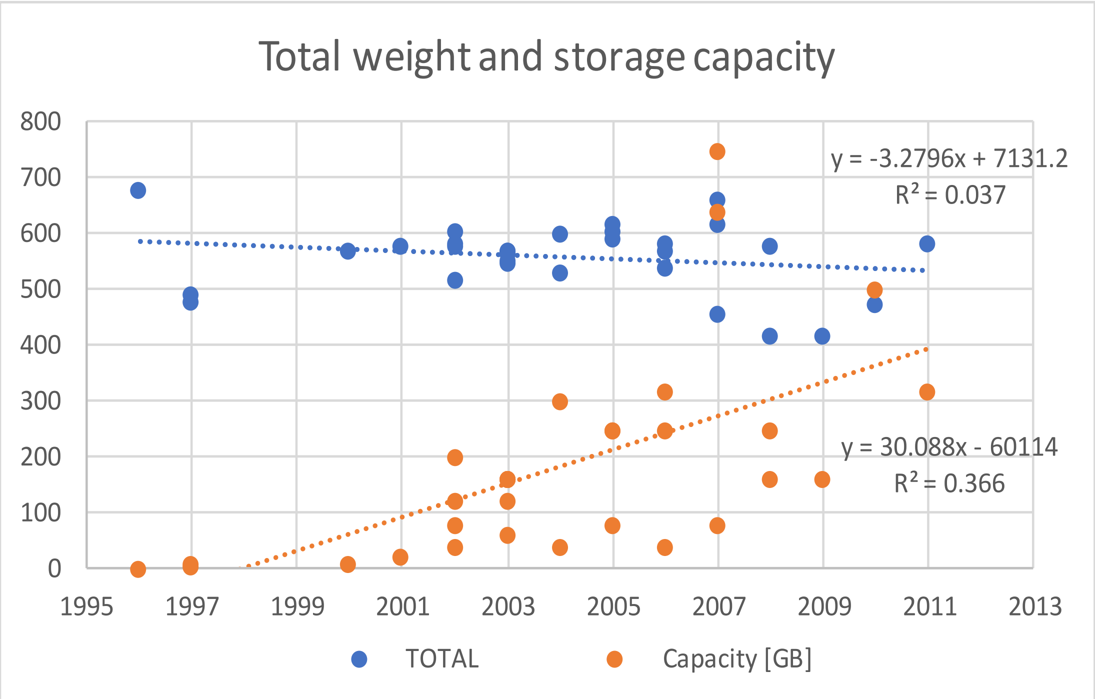


Figure 17: Total weight and storage capacity trends of analysed HDDs (n=31)

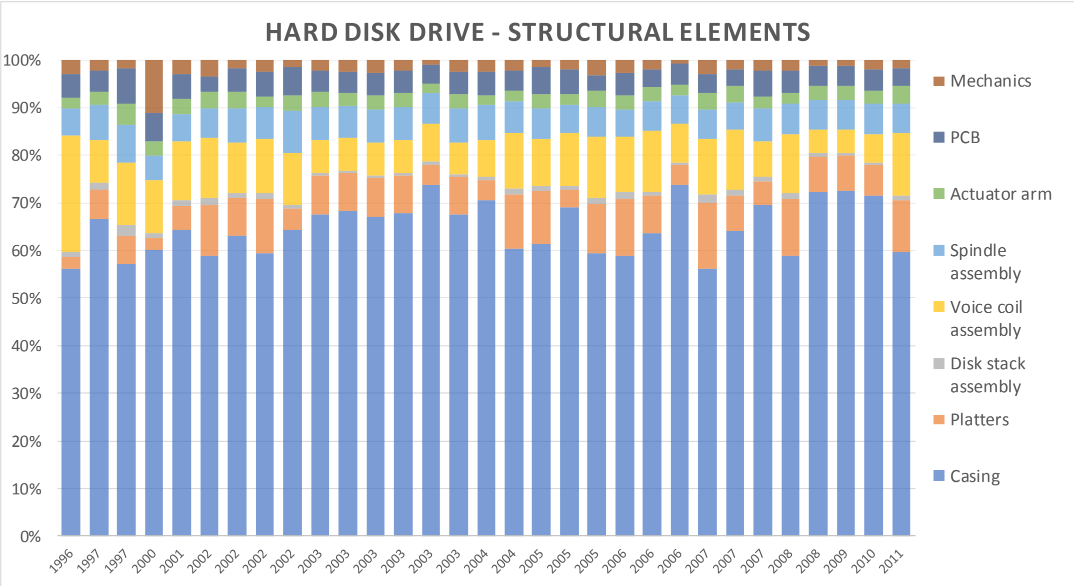


Figure 18: An overview of structural parts of analysed HDDs

Parts summarised under the subcategory disk stack assembly include platters, a spacer between platters, and spindle cover. The platters vary in size and number, from one up to four platter(s) per HDD. The platters have an aluminium core with a very thin layer of a metal alloy containing Cr, Co, Ni, Fe, and Zn, in order to provide magnetic properties necessary for data storage (Habib et al., 2015). By observing all analysed HDDs, an upward trend in weight of the disk stack assembly increase can be observed, which can be explained by the increasing storage capacity and thereby more disk platters.

HDDs have one PCB, which is fixed on the outer side of the casing. From the analysed sample, the PCB weights in average 26,2 ± 5 g. Furthermore, by observing the whole sample, a clear trend in size and weight reduction of PCB can be determined. The mean weight for PCBs from HDDs manufactured between 1996-2002 (n=9) is 29,9 g, whereas the mean weight of PCB from HDDs manufactured between 2007-2011 (n=9) is 22,4 g. A detailed overview of the material composition of PCB from HDDs is shown in Table 9.

Besides PCBs, clear trend in weight decrease has been observed in the subcategories Voice coil assembly (VCA) and mechanics. The subcategory VCA is composed of neodymium permanent magnets and their ferrous metal retainers, whereas the subcategory mechanics includes screws, plastic bumpers, stickers, and plastic pad insulator.

Table 9: Material composition of PCBs from HDDs (Ueberschaar and Rotter, 2015)

Base metals and critical metals [%]											**Precious metals [ppm]**		
Al	Cu	Fe	Ni	Sn	Ti	Zn	Ce	Nd	Sb	Ta	Ag	Au	Pd
2.2	31.6	7.1	2.5	2.4	0.6	0.4	0.5	0.2	0.1	0.8	3,340	1,020	210

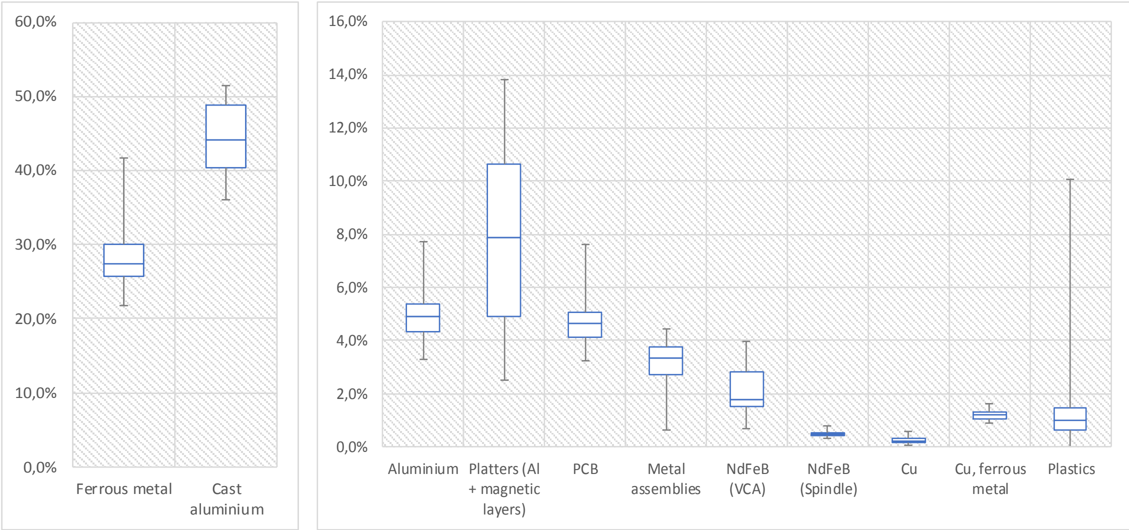
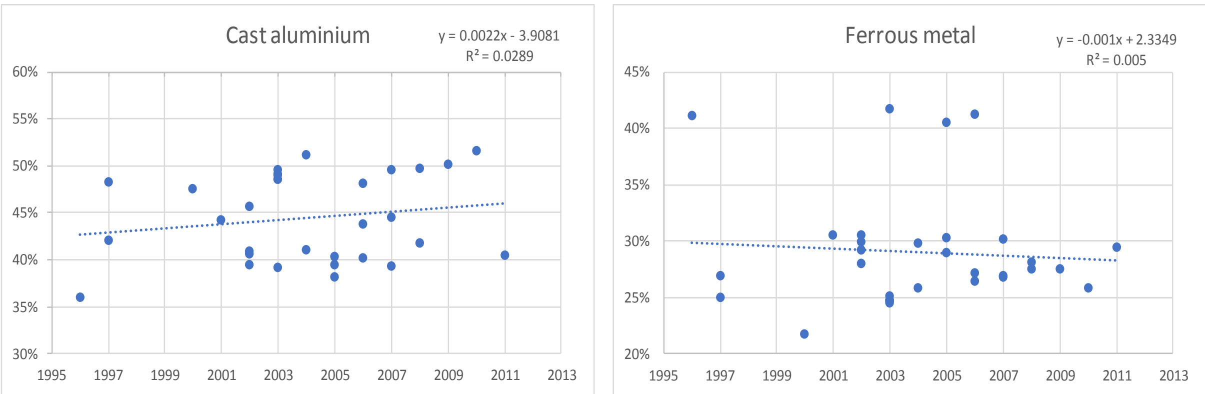


Figure 19: Average material composition of HDDs

From the material point of view, the HDDs are composed mainly of metal parts (over 90 wt.%) and the rest are metal and non-metal assemblies like PCBs, and plastic parts. A summarised overview of the material composition of analysed HDDs is shown in Figure 19. The ferrous metal fraction and the platters are material fractions, which show the highest variations. A cause for the oscillations of the ferrous fraction is due to the fact that the top cover of the housing is sometimes made of ferrous metal and sometimes of aluminium. The cause for the oscillations within platters fraction is due to the fact that the storage capacity of the HDD significantly influences the number of installed platters.

Table 10: Overview of material composition of NdFeB magnets from HDDs (Ueberschaar and Rotter, 2015)

Elements [wt. %]					
Fe	Nd	Pr	Dy	Co	B
64.56	25.3	3.83	2.66	2.42	0.97



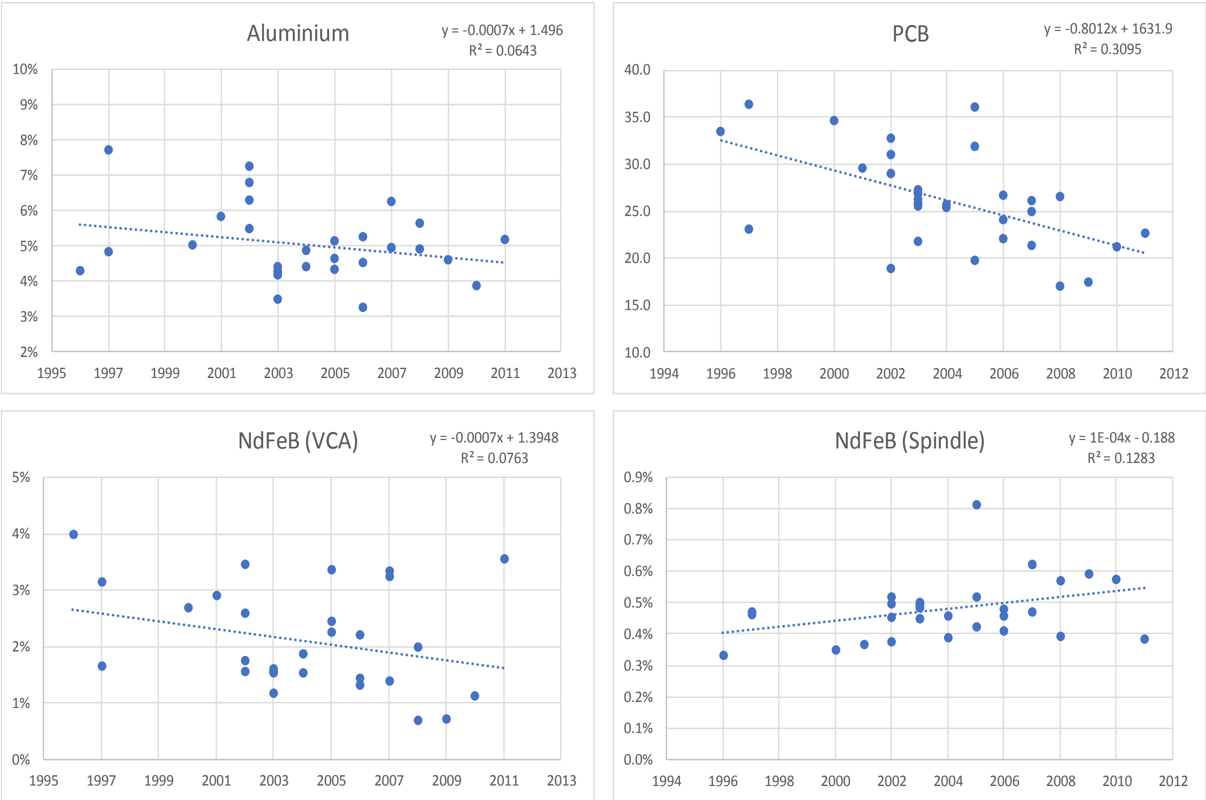


Figure 20: Weight share and trends of selected metals from HDDs

An analysis of chronological mass share development of selected fractions is shown in Figure 20. On the one side, the ferrous metal fraction and cast aluminium fraction have relatively large oscillations, but no significant trend can be observed. On the other side, NdFeB permanent magnet fraction from Voice coil assembly (VCA) show a trend in weight reduction. This trend can also be confirmed by comparing the mean weight of magnets from HDDs manufactured between 1996-2002 (n=9), which is 2,6 ± 0,8 wt.%, and mean weight of magnets from HDDs manufactured between 2007-2011 (n=11), which is 1,9 ± 1,1 wt.%. However, from the variables represented in Figure 20, only the PCB are significant at the 95% level. Furthermore, during the in-depth disassembly, it was observed that the magnets from newer HDDs are noticeably thinner than those from the older HDDs. A detailed overview of the material composition of permanent magnets from HDDs is available in Table 10.

A detailed material and component composition overview for every analysed HDD model are available in Annex I.

3.2 Optical Disc Drives

Within the scope of the research, 15 Optical Disc Drives (ODD) were analysed via in-depth dismantling analysis. The average mass per ODD is 824 ± 134 g. The analysed devices were manufactured between 1995 and 2008. But, three ODDs did not have any designations written on them, so it was impossible to determine their year of manufacture or model. These models were included in the calculations for general parts structure and material composition of ODD but were excluded from the calculations of trend developments.

The ODDs are fairly simple in terms of component complexity and material composition compared to the other complex components. Parts and components comprising ODDs are casing, three different electrical motors, laser assembly, PCB, and mechanical elements. An overview of analysed ODDs with regard to the structural parts and their respective share of the total mass is available in Figure 21.

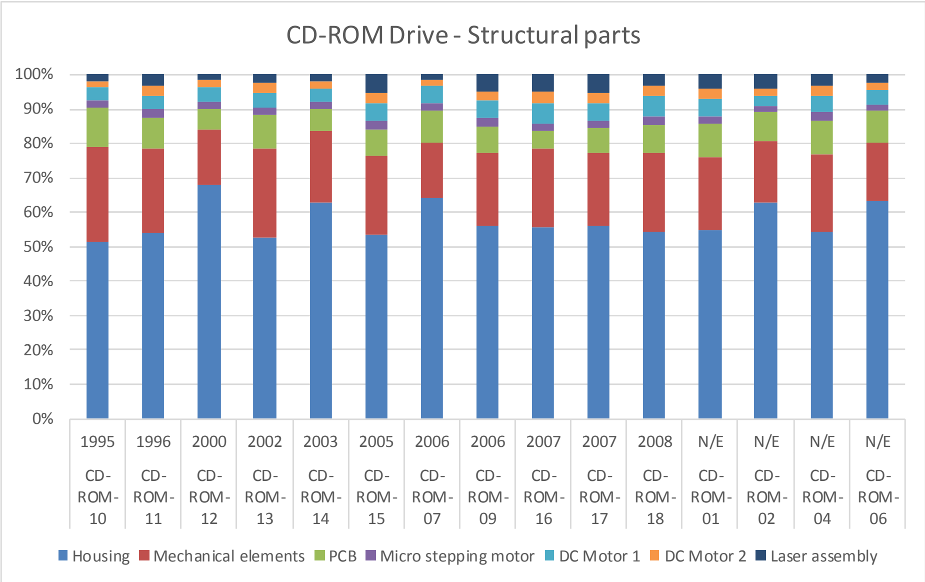


Figure 21: Overview of analysed ODDs (n=15)

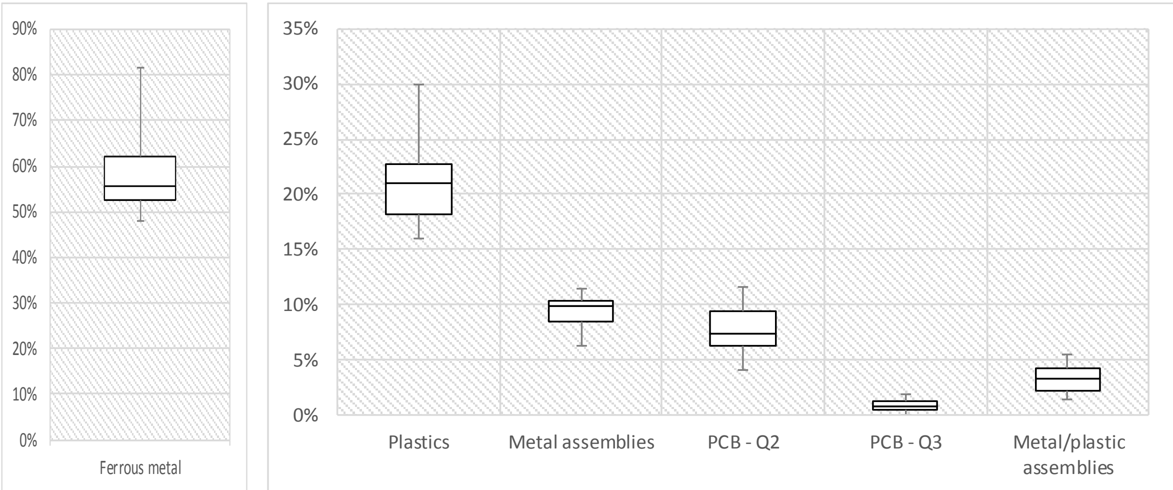


Figure 22: Average material composition of ODDs

Materials constituting ODD can be classified into three groups: ferrous metals, plastics, and material assemblies (e.g. electric motors, PCBs, etc.). The ferrous metal fraction makes in average 57.4 ± 4.9 wt.%, mainly comprising the casing of the drive. The plastic fraction makes in average 21.3 ± 3.3 wt.%. The PCBs make in average 8.3 ± 1.7 wt.% of ODD. The electric motors are made of ferrous metal, copper, small permanent magnet, and other metals. Within the scope of this research, they have been classified as metal assemblies and have in average a mass share of 9.4 ± 1.3 wt.%. The laser assembly is relatively small, but highly complex component made of plastics, ferrous metals, glass, and other materials. The laser assemblies have been classified as metal/plastic assemblies and make in average 3.3 ± 1.3 wt.%. A complete overview of material composition of ODDs is shown in Figure 22.

As it can be observed in Figure 23, a clear trend in decrease of total weight of ODDs manufactured between 1995-2008 can be identified. However, since it was not possible to determine the year of manufacture, four devices have been excluded from the original sample and have not been in any further calculations determining the trends in the material composition of ODDs.

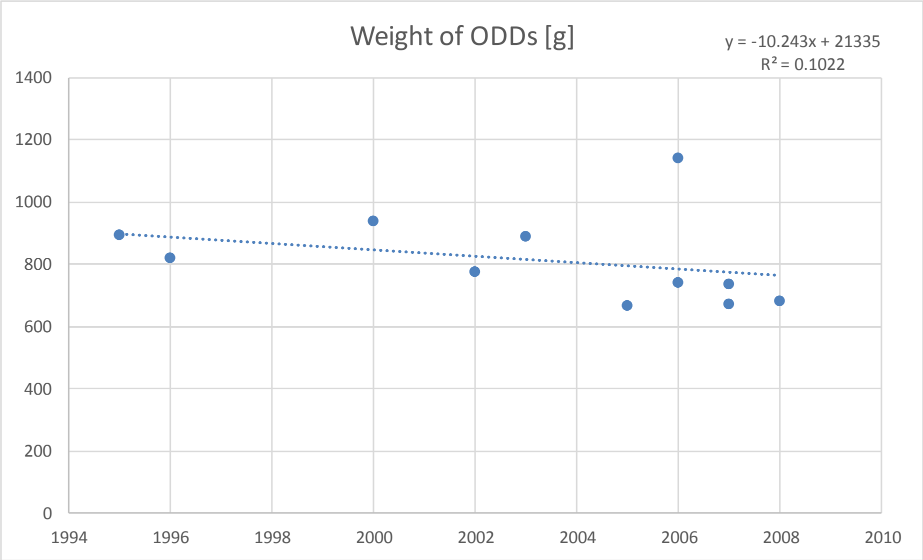


Figure 23: ODD total weight trend development between 1995-2008

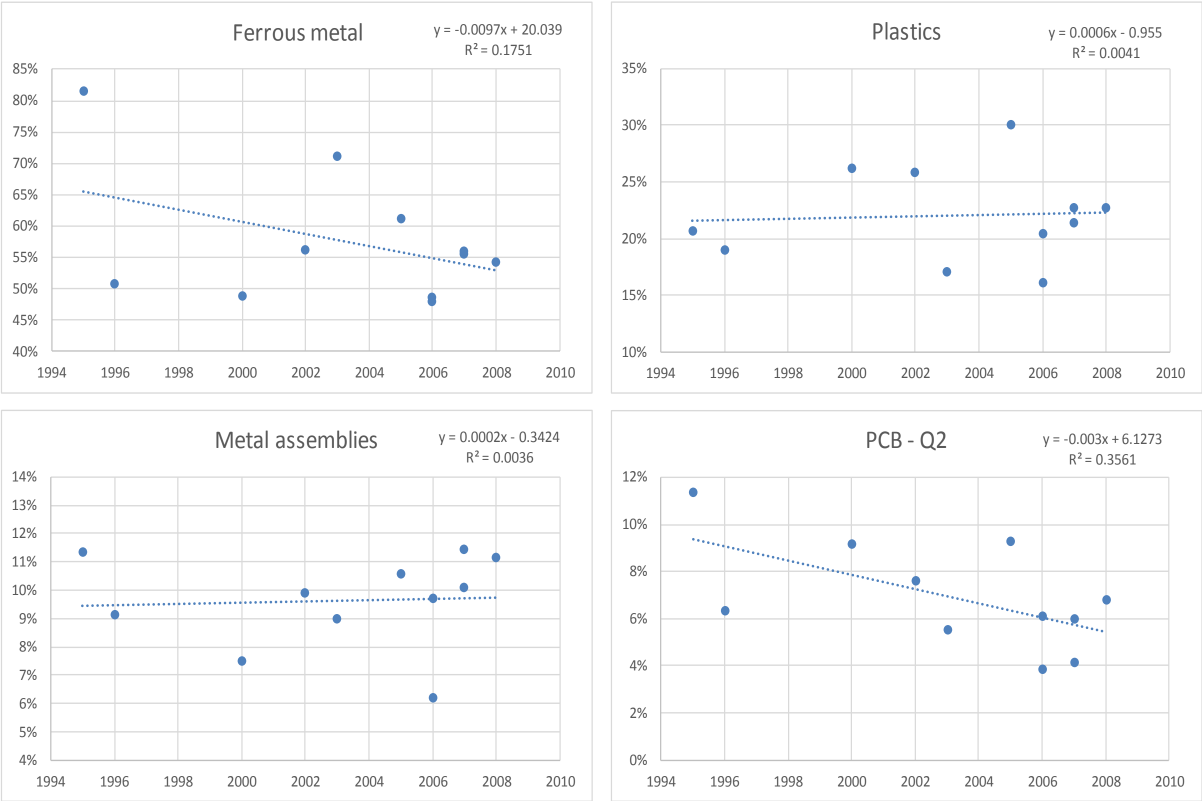


Figure 24: Weight trends for selected material fraction from ODD

In Figure 24 only slight changes in trend can be observed for the mass share for plastics fraction. The plastics fraction is mainly constituted by mechanical parts, which have very little room for eventual technological development and therefore their mass share trend remained almost constant. The ferrous metal fraction shows a distinctive decrease in mass share trend, which can be explained by decreasing volume of ODDs and thereby smaller casing.

The weight of electronic motors remained constant for the considered period between 1995-2008 (c.f. Annex I). However, due to the decreasing trends of other fractions their mass share in total weight is slightly increasing. Finally, the mass share of PCB, in particular, the mass share of Q2 PCBs shows a decrease over time. This trend can be explained by technology development, where the PCBs of newer generations could provide the same functions necessary for normal functioning of ODDs with a smaller size of the PCB. However, it is important to point out, that none of the analysed variables are significant at the 95% level.

A detailed material and component composition overview for every analysed ODDs is available in Annex I.

3.3 Power Supply Unit (PSU-PC)

As part of the research, 10 different Power Supply Units (PSU) originating from desktop computers were randomly sampled at the local recycling company and brought to the further analyses. The analysed PSUs have an average mass of 1460 ± 352 g. An overview of analysed PSU is shown in Figure 25. However, after analysing the results of the analyses, it was not possible to determine any clear trend in change of the total weight for the established time period.

Components composing a PSU are casing, PCB, cables, passive (aluminium) heatsink, active (plastic) fan, and a series of components, which can vary significantly from model to model such as transformers, inductors, switches, etc. In 4/10 PSU, the main transformer was mounted on the PCB, and in the other 6/10 cases, it was built in the PSU as a separate component. If the transformer was present as a separate competent, then it was also weight separately. In all other cases, it was weighted together with the PCB, on which it is mounted.

Elements mounted on the PCB are, by comparison to any other type of PCB, very large. The elements include various capacitors of whom radial style and aluminium capacitors are the largest, several types of electromagnetic coils (e.g. transformers, inductors, etc.), diodes, fuses, and only a few integrated circuits. Furthermore, the PCB from PSU has aluminium passive heatsinks, which were dismounted and weighted separately. All other components represent in terms of material composition material assemblies and were not weighted separately.

The active fans were weight and analysed as separate complex components and the results are presented in chapter 3.4. A detailed material and component composition overview for every analysed PSU-PC is available in Annex I.

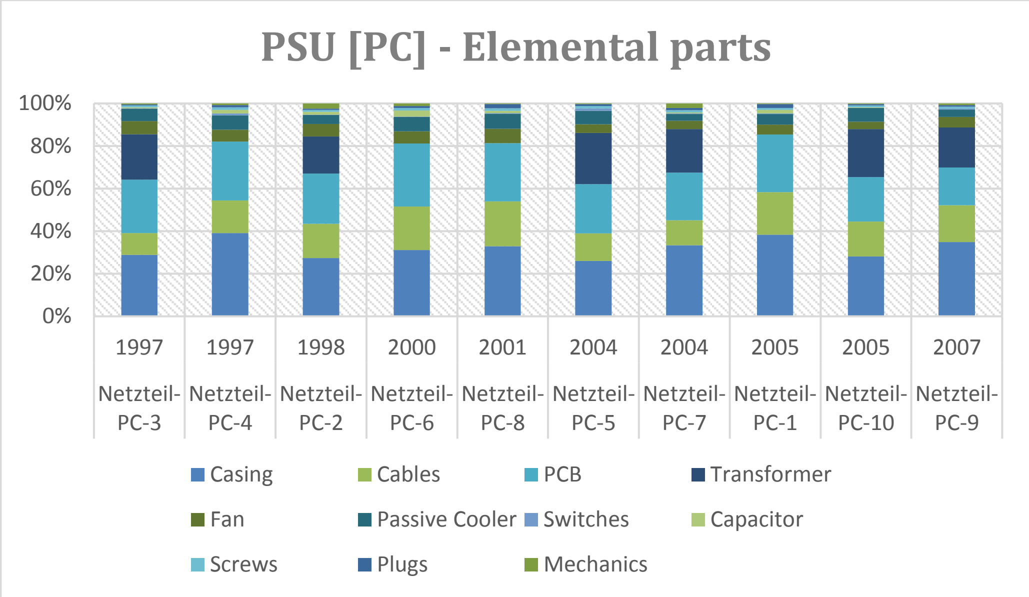


Figure 25: Overview of analysed PSU-PC (n=10)

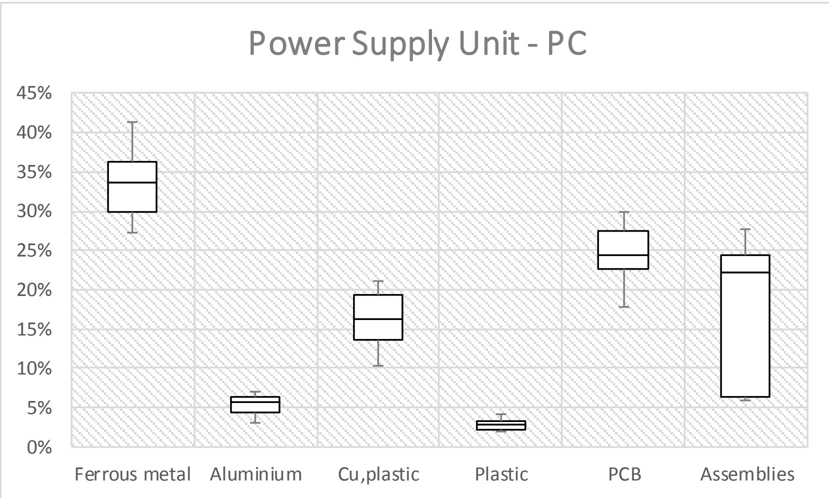
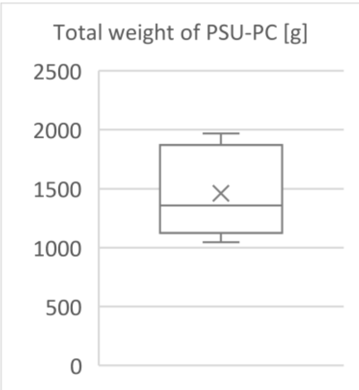
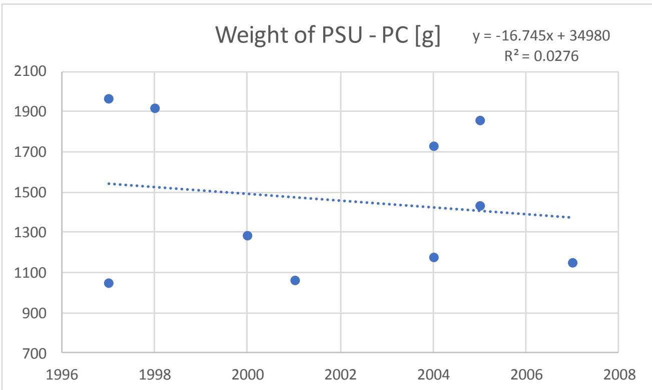


Figure 26: Material composition of Power Supply Units from PCs





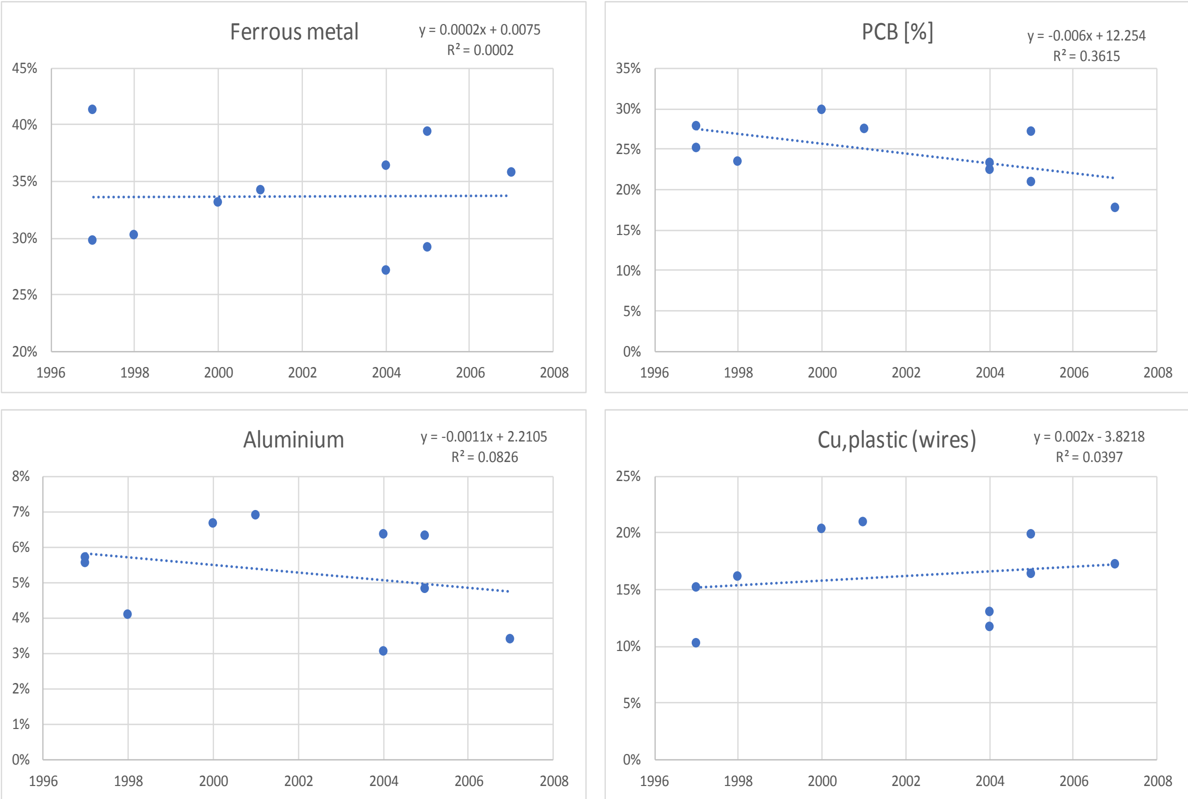


Figure 27: Weight trends for selected material fraction from PSU-PC

In terms of material composition, the largest material fraction of PSU is ferrous metals fraction constituting the casing of PSU. Almost all other material fractions are represented as metal – non-metal assemblies, such as PCB, Cables ("Cu, plastic" in Figure 26), and other. The subcategory "Assemblies" in Figure 26 represent, from a material point of view, also metal – non-metal assemblies and includes transformers, plugs, switches, and other components not mounted on the PCB. As expected, this fraction shows remarkably high scattering rate, due to the irregularity in size and type of the constituting components.

Decreasing trend shows PCB fraction, but if the "Assemblies" fraction is added to the PCB, then the total weight remains constant. Furthermore, the ferrous metal fraction is also decreasing, but only slightly. The Cu-plastic fraction shows a slight increase in the mass share, but the irregularity of the results is also significant. The Aluminium fraction a decreasing trend during the established time period. A graphic depiction of the trends for selected materials is available in Figure 27. None of the above represented variables are significant at the 95% level.

A detailed material and component composition overview for every analysed PSU-PC is available in Annex I.

3.4 Active fans

Within the scope of the research, 11 active (plastic) fans from PSU-PC were analysed via in-depth dismantling analysis. The average mass fan is 67.4 ± 19 g. The analysed fans originate from PSU, which were manufactured between 1997 and 2007.

The active fans are built of following structural elements: housing, propeller, cables, small PCB, and electric motor. An overview of analysed active fans with regards to the structural parts and their respective share of the total mass is available in Figure 28.

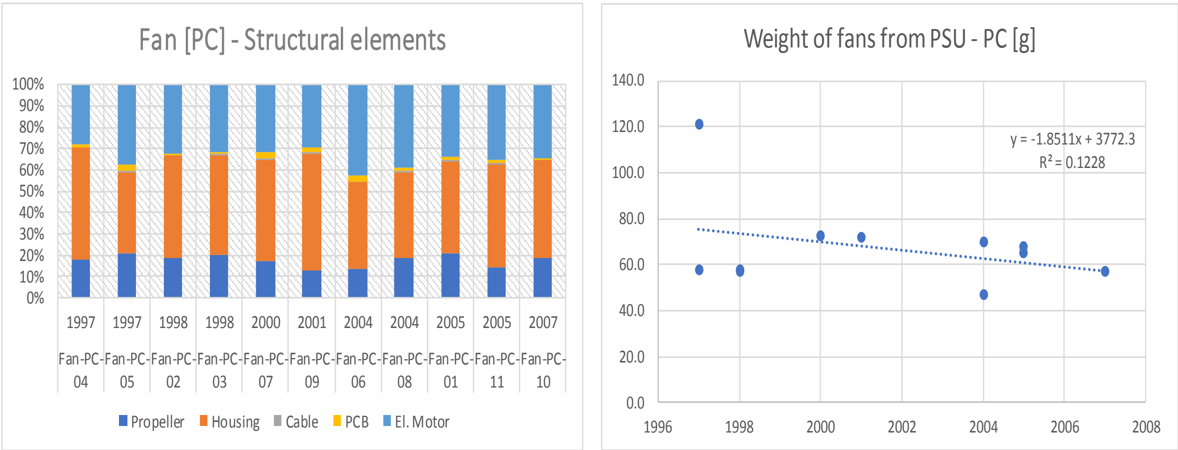


Figure 28: Overview of analysed active plastic fans (n=11)

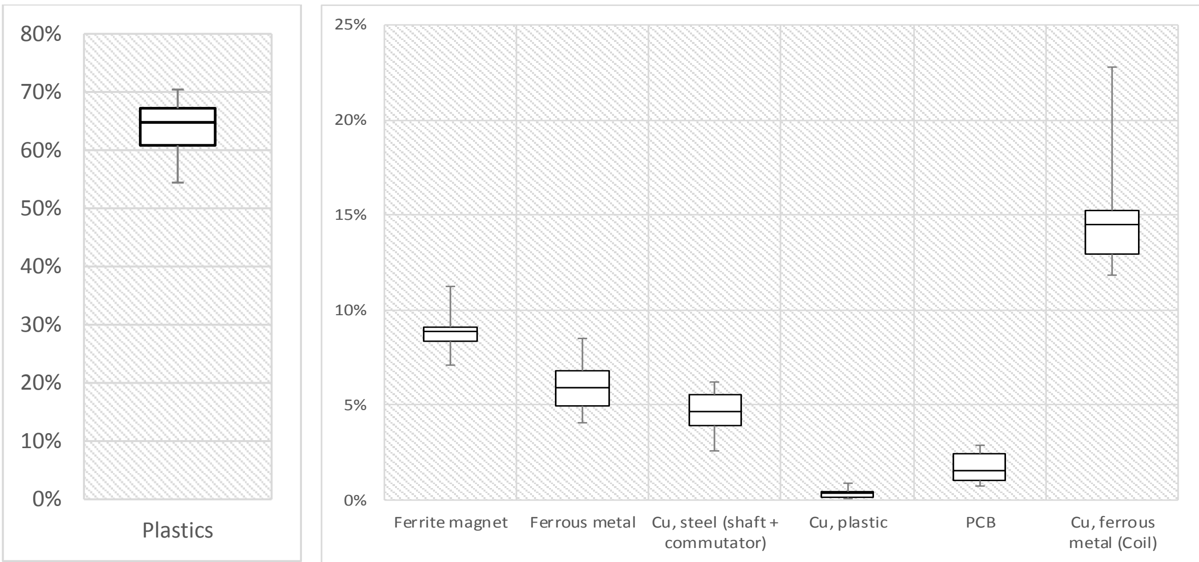


Figure 29: Material composition of active fans

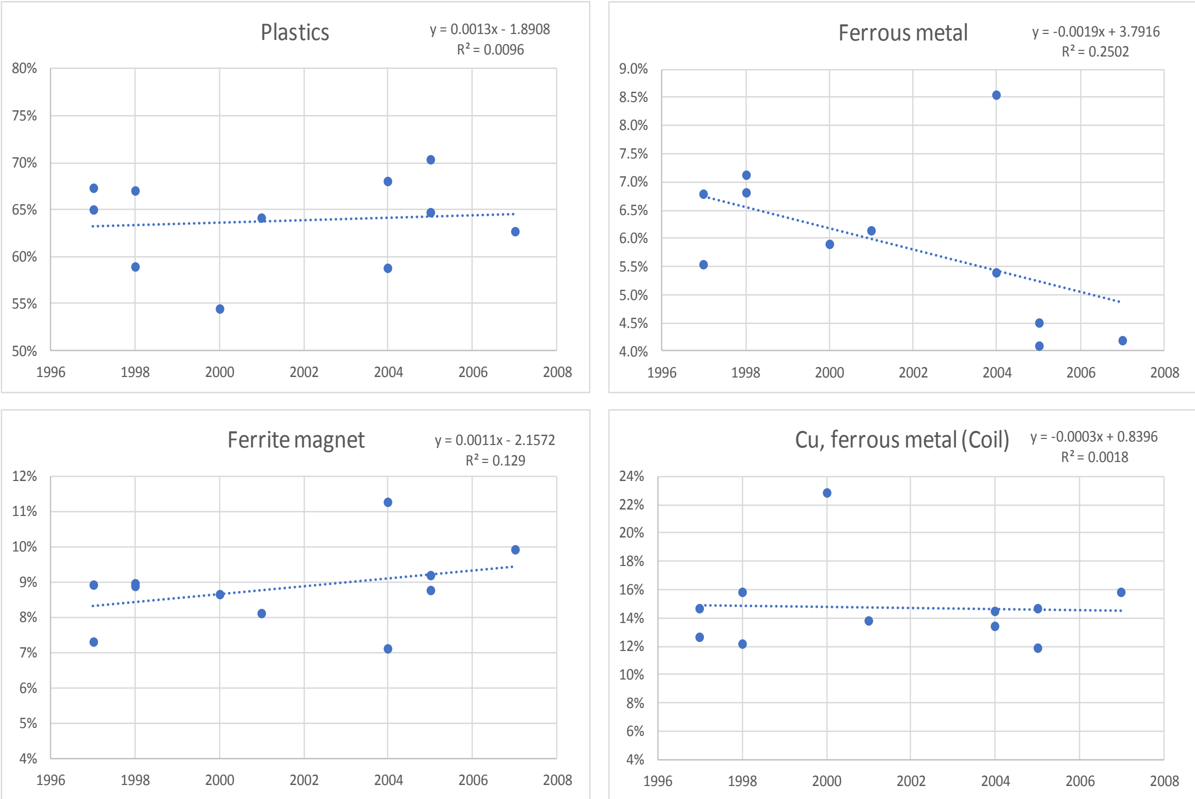


Figure 30: Weight trends for selected material fraction from active fans

With a median value of approximately 65% (38.5 g), by far the largest material fraction of active fans is plastics. It is a building material for housing and propeller. A full overview of the material composition of active fans is available in Figure 29. The plastics is followed by materials constituting electric motor, i.e. magnet, ferrous metal, copper-ferrous assembly.

The electric motors built in the active fans are brushless direct current electric motors, which was determined by means of total disassembly and analysis of the resulting parts. A magnetic frame (or yoke) of the electric motor is made of ferrous metals and it is enveloped in the plastic layer of the propeller. The The permanent magnet is embedded in the magnetic frame. By calculating the density of the magnet and comparing the results with the known permanent magnets, it could be concluded that installed magnets are ferrite (ceramic) magnet (c.f. O'Handley, 2003). The coil is embedded in the permanent magnet, which has winds made of copper and armature made of ferrous metal. The commutator and the shaft are embedded in the coil and they are presented in Figure 29 as the metal assembly subcategory. The shaft is made of ferrous metal, whereas the commutator is made of copper. However, since the shaft is made of steel metal and the coil armature of some other ferrous metal alloy, in the material overview these two fractions were not associated but represented separately.

In Figure 30 are material trends for plastic, ferrous metal, ferrite magnet, and copper-ferrous metal assembly outlined. The plastic fraction and the copper-ferrous fraction do not show any distinctive material development trends in the years between 1997-2007. The ferrous metal fraction shows a decrease in weight share, whereas the magnet fraction slightly increases in the same period. However, from above-represented variables, only the ferrous metal fraction is significant at the 95% level..

A detailed material and component composition overview for every analysed active fan is available in Annex I.

3.5 Power Supply Unit – Printers

Within the scope of the research, 10 Power Supply Units from Printers (PSU-Printers) were analysed via in-depth dismantling analysis. The average mass fan is 176 ± 60 g. However, from the lack of information written on the PSU, it was impossible to determine the year of manufacture. An overview of analysed PSU-Printers is available in Figure 31.

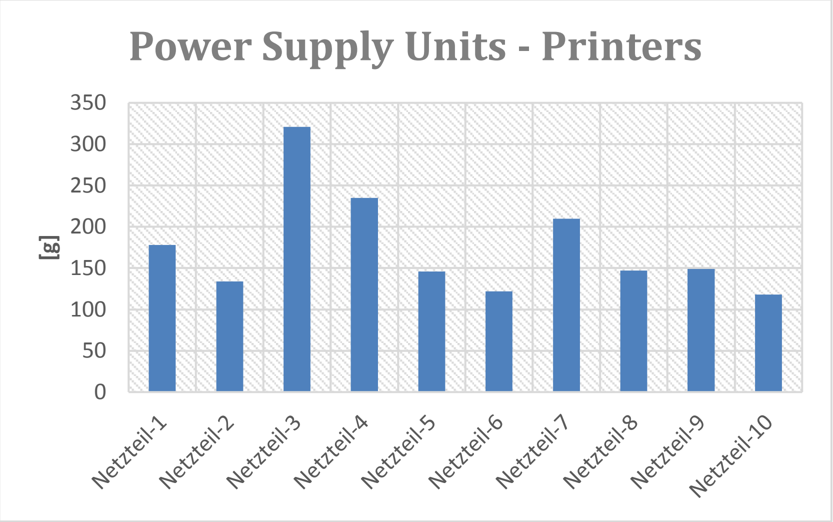
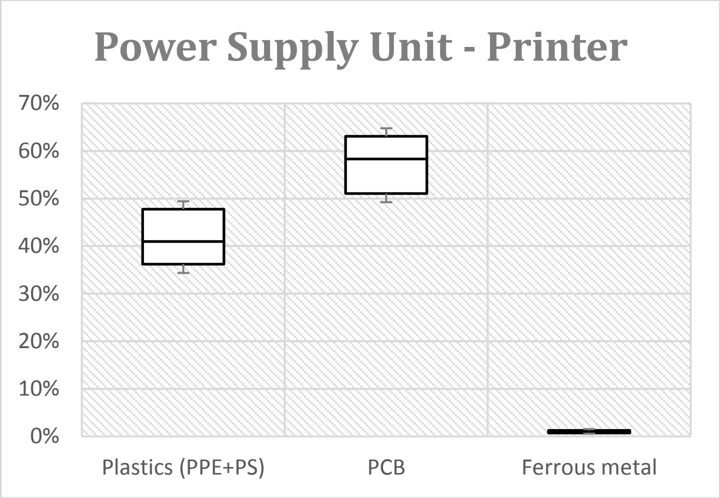


Figure 31: Overview of analysed Power Supply Units from Printers (n=10)

From the component and materials point of view, the PSU-Printers are very simple compared to the other complex components. Essentially, the PSU-Printers are PCB encapsulated in the plastic casing. A cable to and from PSU-Printer was not considered as part of the PSU-Pinter and therefore was not further analysed.

The PCB contains one or two large aluminium capacitors and a couple of smaller aluminium and other capacitors, a relatively large transformer, one or more copper coils and inductors, a plug, and one or two passive aluminium heatsinks.

Materials used for the construction of PSU-Printers were classified into three subcategories: plastics, PCB, and ferrous metal. The ferrous metal fraction is constituting material for a screw(s) keeping the casing of the PSU-Printers fixed. A material composition and range of individual material fractions are available in Figure 32. A detailed overview for each PSU-Printer is available in Annex V.



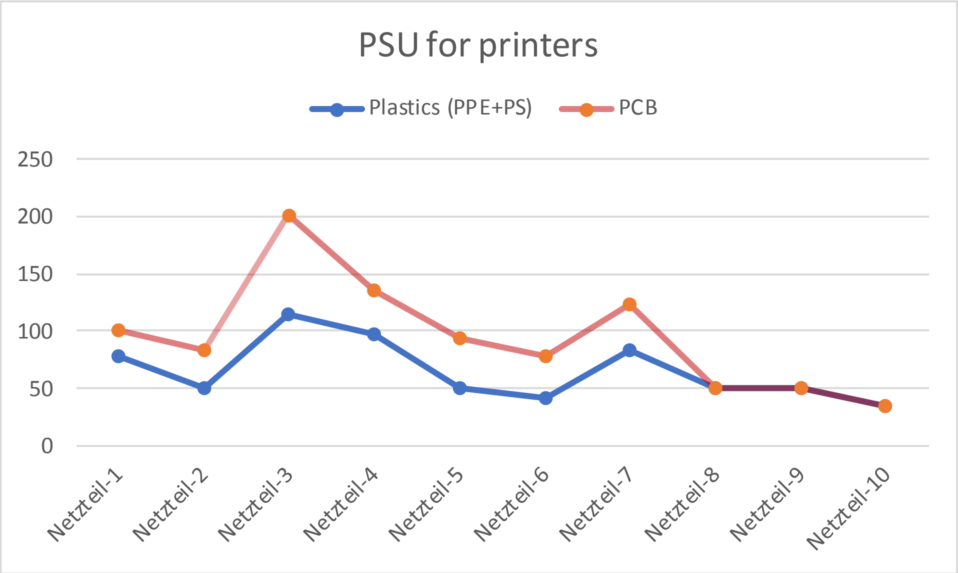


Figure 32: Material composition of PSU-Printers

3.6 Results of ICP-OES analysis

In addition to the in-depth disassembly and simple material identification analysis, was also an analysis of trace metals from aluminium capacitors from motherboard PCB carried out. The analysis was conducted by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The analysis of Al-capacitors via ICP-OES included 10 different capacitors (< 15 mm) originating from a “mainboard” type of PCB from PC. The capacitors were organised into two sample sets and subsequently analysed via ICP-OES for trace metals. In

Table 11 are summarised trace elements, which have been analysed within the scope of ICP analysis and their wave lengths (nm). The most suitable wave length for a respective element has been determined by identifying four different peaks within the spectrum of the selected element and then repeating the analysis five times at the each of these wave lengths. The wave lengths with lowest standard deviation and residual standard deviation (%RSD) have been included in the final results of the ICP-OES analysis. Calibration curves for selected elements have been calculated and are available in Annex II.

Limits of detection (LOD) and limits of quantification (LOQ) have been calculated according to the standardisation developed by European Medicines Agency (EMEA, 1995). Both LOD and LOQ have been calculated based on the calibration curves (S) and the standard deviation (σ) of respective elements, as following:

$$LOD = \frac{3.3 \times \sigma}{S} \quad (1)$$

$$LOQ = \frac{10 \times \sigma}{S} \quad (2)$$

Table 11: Spectral lines for elemental analysis with ICP–OES

Trace metals	Wave length (nm)
Au	242.7
Cd	226.5
Fe	239.5
Ni	221.6
Pb	220.3
Ti	323.4
Zn	206.2

Table 12: Calculated limits of detection and quantification for respective elements

Trace metals	Procedure 1		Procedure 2	
	Limit of **detection [ppm]**	Limit of **quantification [ppm]**	Limit of **detection [ppm]**	Limit of **quantification [ppm]**
Au	1.2	3.8	1.2	3.8
Cd	0.1	0.2	0.1	0.2
Fe	0.1	0.3	0.1	0.3
Ni	0.1	0.3	0.1	0.3
Pb	0.0	0.1	0.0	0.1
Ti	0.1	0.3	0.1	0.3
Zn	0.1	0.2	0.1	0.2

Table 13: Results of ICP-OES analysis for sample sets 1 and 2

	Sample set 1		**Sample set 2**	
Element	[ppm]	ICP %RSD	[ppm]	ICP %RSD
Au	785	5.30	684	7.16
Cd	0	0.11	0	0.07
Fe	13,085	0.70	12,223	1.24
Ni	0	0.34	0	0.26
Pb	0	0.84	0	0.56
Ti	1,112	2.16	3,045	0.58
Zn	6	0.73	1,294	0.29

The results of ICP-OES analysis show that by far the highest concentration has Fe with an average mass 1.3 % for the sample set 1 and 1.2% for the sample set 2. The elements Cd, Ni, and Pb could not be detected neither in the sample set 1 nor 2. The Zn fraction has been detected in a very low concentration in the sample set 1 with 6 ppm, but in significantly higher concentration (app. 1300 ppm) in the sample set 2. Even though all analysed Al-capacitors are of their weight, shape, size very similar and originate from the mainboard PCB manufactured in the same year. The root cause for these differences lays probably within different solubility of Zn depending on the digestion procedure.

Furthermore, Au fraction shows also interesting results with relatively high concentrations of the app. 790 ppm and 680 for the sample set 1 and 2 respectively. Therefore, the observed Au concentration is similar or higher than the average concentration for the whole mainboard PCB (c.f. Chancerel et al., 2013, Cui and Zhang, 2008, Yamane et al., 2011).

4. Summary

The aim of the master thesis was to determine the material composition of complex components from WEEE and to develop a suitable analytical procedure for the analysis of complex components from WEEE. Within the scope of this research, three methods have been combined in order to achieve this goal. First, a comprehensive literature research was carried out to assess the current situation of the technological development and functionality of analysed components. Second, a set of the simple material identification analytical test has been arranged in a novel analytical procedure for identification of at least eight different base metals has been established. This simple material identification analysis is combined with the in-depth disassembly in order to determine the material composition of complex components from WEEE on an example of groups of complex components: hard disk drives, optical disc drives, power supply units (PSU) from PC, PSU from printers, and active fans. Finally, Inductively Coupled Plasma Optic Emission Spectroscopy (ICP-OES) as an advanced analytical procedure appropriate for an analysis of a variety of different metals and non-metals, but also limited to very small sample sizes. It is suggested, to use ICP-OES anylsis for parts of complex components with a highly complex material composition, whose further dismantling would not lead to better results. Furthermore, the ICP-OES analysis is recommended for components containing precious metals Rare Earth Elements (REE), which are usually found in very low concentrations. Within the scope of this research, aluminium capacitors from motherboard PCBs have been analysed to exemplify the use of ICP-OES analysis.

The complex components are sorted out in a de-pollution process as part of the pre-processing of WEEE. The analysed components were obtained in a local recycling company, which uses manual dismantling for carrying out a depollution step. The sorted out complex components are then further treated in accordance with the legal requirements for treatment for hazardous waste defined by WEEE Directive 2012/19/EU and RoHS Directive 2002/95/EC.

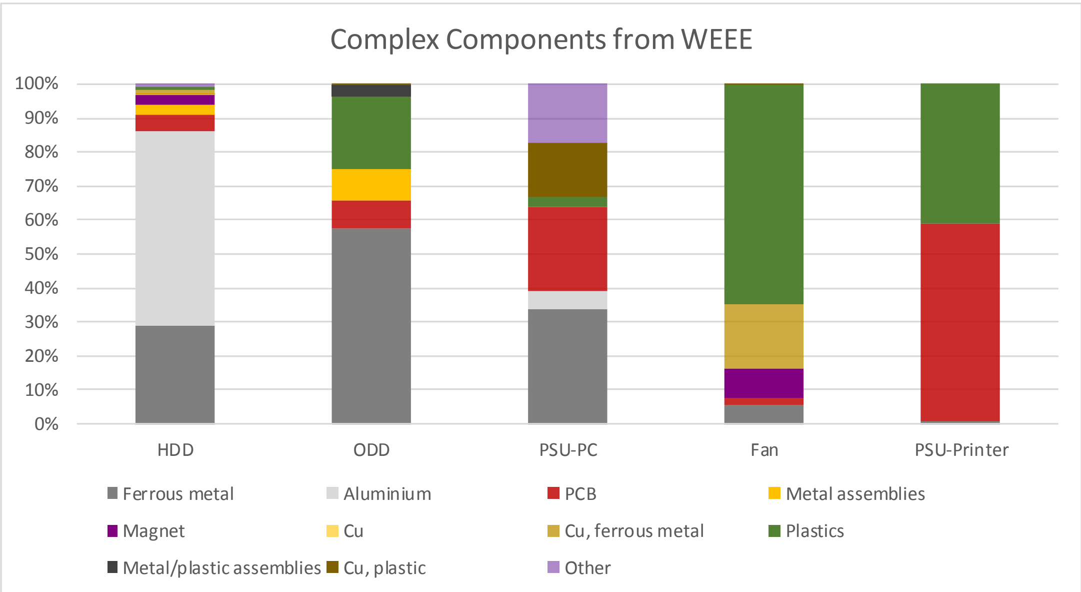


Figure 33: Material composition of all analysed complex components from WEEE

The results of an in-depth dismantling and a subsequent simple material identification analyses show that this analytical procedure is well suited for the analysis of complex components from WEEE. Using this method, it is possible to identify over eight different base metals or more than ten different materials. Mean material composition of all analysed complex components from WEEE is available in Figure 33.

For the **Hard Disk Drives (HDDs)** it was possible to associate over 90 wt.% of dismantled parts to homogenous materials and subsequently to identify these materials using simple material analysis. The results show that the total weight of HDD in the period between the years 1996 and 2011 has a decreasing trend. As it was expected, and thus by reassuring the representativeness of the sample, in the same period a storage capacity has greatly increased. Furthermore, the results of the analysis show that the predominant materials are cast aluminium and ferrous iron. Both fractions show only a slight variability and no distinctive trend in the material composition was determined for the established time period. Materials, which show distinctive changes in the material composition, are Nd magnets, both spindle and VCA magnets, an aluminium fraction other than HDD casing, and a layered aluminium alloy of the disk platters. After examining the sample, it was observed that the VCA magnets are becoming thinner and that the VCA contain only one magnet in the more recent HDD models. Along these lines, the VCA magnets show a decreasing trend starting from 2.5 wt.% and finishing at almost 1.5 wt.% during the established time period. Unlike VCA magnets, the spindle magnets show a slight increasing trend for the same period. The weight share of disk platters increases with the increase of the storage space, despite the increased data storing efficiency. The results of the in-depth disassembly show that the weight share of disk platters increased from 6 wt.% almost up to 10 wt.%.

According to Wood (2009), features of the HDDs, which have the highest potential for further development, are controlled atmosphere within the HDD and a data transfer rate. The controlled atmosphere within the HDD involves introduction of an inert gas, most likely helium, in order to improve robustness toward the altitude changes and reduced susceptibility to corrosion. The improved data transfer rate would include an improved coupling between a read/write heads and a preamplifier (c.f. Wood, 2009). However, these changes would not have a significant influence the currently prevailing material composition of HDD. For these reasons, it can also be assumed, that the material composition will also not change significantly in the medium-term future. This gives an opportunity for the recycling companies to optimise the recycling technology of HDD of the maximal effectiveness.

The components of special interest for the recycling industry are those, which contain either precious metals, e.g. gold, silver, platinum, etc., or rare earth elements (REE), e.g. europium, neodymium, yttrium, etc. In the HDDs, components containing these metals are VCA and spindle magnets containing for containing neodymium, PCB for containing gold, silver, and other precious metals, and connectors between a read/write head and a preamplifier on an actuator arm for relatively high gold concertation. Furthermore, the shape and the function of VCA magnets has not changed during the established time period and they are easy and quickly accessible during the dismantling process without losing their magnetic properties. For these reasons, the VCA magnets have very high potential for re-use instead of recycling.

After taking into account a technological development of HDDs, described in detail in the chapter 2.1.1, and despite the emergence of novel technological solutions for data storing, e.g. Solid-State-Drive, Cloud storage, etc., it can be safely assumed based on the data storing stability of HDDs on the one hand, and a production cost-effectiveness on the other, that the HDDs will not become obsolete in the medium-term future

In the time period between the years 1995 and 2008, the analysed **Optical Disc Drives (ODDs)** show clear decreasing trend of a total weight. The materials constituting ODDs can be broadly subdivided into three groups: ferrous metals, plastics, and material assemblies. Components made of ferrous metals and plastics generally have mechanical functions, e.g. casing, screws, disc tray, gear wheels, etc. Both in terms of material composition as well as technologically, the components constituting material assemblies are the most complex part of the ODD. The components constituting this subgroup include three electrical motors, laser assembly, and printed circuit boards (PCBs). The results of the in-depth disassembly show that two fractions, i.e. the ferrous metal and PCBs, show strong decreasing trends in the established time period and thereby causing the reduction of total weight of the ODDs. The absolute weight of the electric motors and laser assembly remained fairly constant, but since the total weight of the ODD is decreasing, their relative wt.% is increasing. The plastics fraction remained fairly constant between 20 – 25 wt.%.

Unlike HDDs, the technological evolution of ODDs had a considerably higher influence on the storing medium, which is in the case of ODDs removable from the drive. As a result, formats such as CD, DVD, Blue-Ray, etc. were developed (c.f. chapter 2.1.2). In the drive itself, the laser assembly and in particular read/write laser and optical sensor were subject to the principal technological development. However, these technological developments had only marginal effects on the material composition of these components (c.f. Taylor et al., 2006, Pressyanov et al., 2015). In contrast to laser assembly, the technological development of integrated circuits (IC), or more specifically, the technological development of semiconductors, made a reduction of the size and the number of mounted ICs on the PCB possible (c.f. Lee et al., 2009).

The components of special interest from ODDs, which meet the previously defined criteria, are electric motors for containing a permanent magnet, laser assembly for containing REE, and PCB for containing REE and precious metals. Plastic mechanical parts, e.g. gear wheels and other, and electrical motors have high potential for re-use, since they are very easily accessible during the dismantling procedure and preserve the quality characteristics very similar to the new components.Despite the technological maturity, reliability, and cost-effectiveness, the ODDs have been increasingly marginalised by the new storage technologies, e.g. solid-state drive, cloud storage, etc., and do not appear as part of the standard equipment for many laptop models. Therefore, further development of the existing recycling technologies for ODDs seems from this perspective superfluous.

10 **Power Supply Units from PCs** (PSU-PC), manufactured between the years 1997 and 2007, were dismantled by the in-depth disassembly and analysed by the simple material identification analysis. After analysing the results of analyses, it was not possible to establish any clear trend of total weight for the established time period. The structural elements of the PSU-PC include following components: a ferrous metal casing, a PCB, (active) fan, and wires. The results of the analyses show that only two material fractions show clear trends. Namely, the “Aluminium” fraction shows the decreasing trend, and the “Cu, plastics”, which designates the wires, show increasing

trend. All other material fractions remain fairly constant and therefore confirm the trend of the total weight of PSU-PC.

The change in the material composition of PSU-PC is more significantly influenced by the differences between higher and lower quality models than by the technological development. By means of in-depth disassembly and subsequent material identification analyses, it was not possible to determine any significant changes in the material composition, which could be attributed to the technological development.

The components of special interest from PSU-PC, which meet the previously defined criteria, are a plate of the PCB for containing precious metals and capacitors, rectifiers, diodes, and filters for containing REE. Due to the fragility of the mounted components on the PCB in the PSU and low market price of other components (e.g. casing, wires, etc.), their re-use potential is very low.

In total, 11 **active fans** from PSU-PC manufactured between the years 1997 and 2008, were analysed using the same procedure as previously described. Although larger fans show better performance compared to the smaller ones (Torres, 2008), the results of the analysis do not show any definitive trend in the total weight of the fans. The dominating material is plastics with approx. 65 wt.%. The plastics contains also flame retardants, which was concluded by the engravings on several models from the sample. The identification and quantification of the contained flame retardants exceed the scope of this research. Besides plastic parts, the fans from PSU-PC contain also a brushless electrical motor, which makes the residual weight of the fan. Therefore, a ferric magnet fraction is relatively high and makes in average approx. 9 wt.% of the fan. The copper/ferrous metal fraction (or copper coil) makes in average 15 wt.%, whereas the homogenous ferrous metal fractions make in average 6 wt.% of the fan.

The material fractions of special interest for their market value from PSU-PC fans are ferric magnets and copper fraction, which is contained in the copper coils, in the commutator, and in the wires. However, due to their fragility and relatively hard accessibility via in-depth dismantling, their re-use potential is very low.

10 **Power Supply Units from printers** (PSU-Printers) with unknown years of manufacture, were analysed using the same procedure as previously described. The PSU-Printers have a simple structure compared to the other analysed complex components. The results of the analysis show that a plastic fraction is in average approx. 40 wt.% and a PCB, with all mounted components, has in average approx. 60 wt. %. However, the identification and quantification of the contained flame retardants exceed the scope of this research.

The components of special interest from PSU-Printers, which meet the previously defined criteria, are capacitors, diodes, and filters for containing REE and a PCB plate for containing the precious metals. As it with other complex components, the elements, mounted on the PCB perform complicated functions and they are fairly fragile, which reduces their re-use potential significantly. However, the passive aluminium heatsinks (or passive coolers) could be quickly dismantled from the PCB without losing their properties.

Currently, there are indications that the PSU-PC, PSU-Printers, or any of their components could become technologically obsolete or to be replaced by some now technological solution (c.f. Torres, 2006, Kirsch, 2005a, Mpitziopoulos, 2015). For this reason, expending of the current recycling technology of PSU-PC is potentially advantageous.

Limits of in-depth disassembly and subsequent simple material analysis become apparent when dealing with highly complex elements, e.g. integrated circuits, copper coils, capacitors, etc., wires and with analysis of precious metals, or REEE. The wires and integrated circuits, capacitors and other components mounted on a PCB have many different materials, both metal and non-metal, concentrated on a very small space and therefore their separation is highly impractical and near impossible by in-depth disassembly. The precious metals and REE are usually existent in electronic components in very low concentrations and as part of a complex alloy with other metals, so their identification is impossible using simple analytical methods. In these cases, it is recommended to combine the in-depth disassembly with an another more advanced analytical technique, e.g. with ICP analytical technology..

Inductively Coupled Plasma Optic Emission Spectroscopy (ICP-OES) analysis was carried out to analyse aluminium capacitors for the motherboard PCBs as an example for a recommended analytical procedure for the complex components. Since it was possible to determine the basic material composition of aluminium capacitors, the ICP-OES was used in order to quantify trace metals, i.e. Au, Cd, Fe, Ni, Pb, Ti, and Zn. The results of the ICP-OES analysis show that the Fe fraction with approx. 13,000 ppm and 12,200 ppm for digestion procedure 1 and 2, has by far the highest concentration of the analysed metals. The Fe fraction is followed by Ti with average concentrations of approx. 1,100 ppm and 3,000 ppm, and Au fraction with approx. 780 ppm and 680 ppm for digestion procedures 1 and 2 respectively. The results for Au concentration have been surprising because these results are higher than an average Au concentration for the whole PCB motherboard (c.f. Cui and Zhang, 2008, Sorger et al., 2014, Kasper et al., 2011). The Zn fraction shows extremely large variability between the two digestion procedures. The digestion procedure 1 with 6 ppm beardly reaching the quantification limit, whereas the digestion procedure 2 shows approx. 1,300 ppm concentration. Finally, the fractions Cd, Ni, and Pb are either not existent or have concentrations below 1 ppm.

The variability of results of ICP-OES analyses confirms the assumption that the electronic equipment is highly challenging material for this analytical technique. In order to increase the precision and replicability of the results, through steps need to be undertaken to reduce the variability. For better results, it is recommended identify the general material composition of the sample with simpler analytical procedures, e.g. simple material analyses, prior to the ICP analysis and to limit the ICP tests on only few elements per analysis and to reduce, as much as it is possible, the concentration range of the analysed elements and thereby avoiding the analysis of the elements, whose concentrations in the sample differ by several orders of magnitude.

5. Discussion

Due to the rising quantities, high economic potential, but also high environmental impact, the material composition of WEEE and especially PCBs has been the focus of research since the beginning of 1990-is. However, the results of analyses of material composition tend to be highly irregular, so that their comparability, practicality, and overall value are also limited. There are multiple causes for this situation in the scientific literature. First and foremost, there is a lack of sufficient description of the analysed material. This shortcoming was especially apparent from the beginning of 1990-is and for the next 20 years. Furthermore, closely related to the first problem is an insufficient description of the conducted analyses. Finally, the electrical and electronic equipment has an extremely high variety of models and have been developing with the astonishing rate from the 1990-is onward, which hinders the development of standards for WEEE analysis.

The research of Sum (1991) is one of the first, but also one of the most influential papers published in high impact scientific journals on the material composition of PCBs. The paper covers most important segments regarding recycling of PCBs, beginning with the material composition, pre-treatment, end-treatment, and an overview of the scientific literature on this subject. And yet, the paper achieved the highest resonance in the scientific literature with publishing one of the first complete material compositions of metals from PCBs. Nonetheless, the paper contains also several overviews, which are also adopted in the scientific literature by various other authors as well. First, there is a confusion in defining the research object. The author refers throughout the paper to the “electronic scrap”, but after closer examination and comparison to similar papers, it is assumed that under the term “electronic scrap” it was referred to the motherboard PCBs from PC. Furthermore, any other information about the analysed samples, e.g. year of manufacture, digestion method, what equipment was used for the analysis, are missing. Despite these circumstances, this paper is one of the most influential papers published on this subject, due to early recognition of the problem, its comprehensive scope, and its overall relevance in the scientific literature. Similar papers were later published by Zhang and Forssberg (1997), Veit et al. (2002), and Ernst et al. (2003).

From the mid-2000s, the focus of the scientific research expanded from the material composition of PCBs from PC to the material composition of entire devices. In this sense, another milestone represents the report by Huisman et al. (2007) published by the United Nations University (UNU). This extensive study contains a review of WEEE in correlation to the WEEE Directive 2002/96/EC. The report has a review character, where the majority of the provided material compositions of WEEE were carried out and published by other authors. The published material compositions were not classified according to the devices, but for the entire categories defined by the WEEE Directive 2002/96/EC, and therefore it is not possible to narrow down the material composition to a single device. As it was the case with other similar publications, the report is missing the information about the analysed samples, e.g. background information of devices, or overview of the analytical procedure. Similar scientific papers, but smaller in scale, were written by Cui and Zhang (2008), Ogunniyi et al., (2009), Williams (2010), Oguchi et al. (2011), and Holgersson et al. (2017).

Scientific publications focusing on the specific components from the WEEE have been very scarce so far. However, in the last ten years, securing of alternative sources of REE became prominent in the EU, so accordingly the scope of scientific research expanded to the devices or components containing these elements. Since these materials are usually present in the WEEE in very low concentrations, the traditional focus of research, which relied either on the material composition of PCBs or on the material composition of devices or even whole categories, was not sufficient anymore. These incentives resulted in increased interest in the material composition of HDDs since they contain large permanent magnets and therefore relatively high concentration of REE. Ueberschaar and Rotter (2015) published a paper on the material composition of HDDs. Unlike the prevailing situation in the scientific literature, this paper includes detailed information on the sample size, analytical procedures, and material composition deviations. The sample includes in total 43 HDDs from PC with an average weight of 554 g, which is very also very close to the average weight of 559 g analysed within the scope of this research. Furthermore, Ueberschaar and Rotter (2015) followed the similar analytical procedure described in this research. After in-depth disassembly, the base metals have been analysed using XRF (X-ray fluorescence) method, but the magnets and the PCB were analysed with an ICP-MS. The results show very similar average wt.% for PCB, magnets, and plastics fraction. However, the results for ferrous metal fraction show relatively lower values in the analysis of Ueberschaar and Rotter (2015) compared to this research. Similar studies focusing on the material composition of HDDs were published by Sprecher et al. (2014), Habib et al. (2015), and München and Veit (2017).

Metals constituting complex components can be classified into three groups: base metals, precious metals, and REE. The base metals subcategory has the lowest market value of the three and therefore are available in the complex components in high concentrations. The base metals are usually building material for components, which perform relatively simple functions, as for example casings, mechanical components, e.g. screws, spindles, lids, etc., passive heatsinks, wires, coils, and similar. Furthermore, they are in most cases easily accessible by in-depth dismantling and can be identified and quantified using the simple material analysis.

The **precious metals**, above all gold, silver, and palladium, are available in the electronic equipment very small concentrations compared to the base metals. Their market value is also several orders of magnitude higher than of the base metals. The precious metals are used in the electronic equipment due to their outstanding electrical conductivity, durability, and their corrosion resistance. Therefore, the precious metals can be found in the connector pins, fingers, plugs, and generally in PCBs connecting various components to the conductivity layer. Besides being in small concentrations, the precious metals are also usually smelted in alloys with other base and/or precious metals. For these reasons, the analysis of precious metals fairly complicated and cannot be carried out by the simple material analysis. The recommended procedure for the analysis of precious metals is ICP.

The **Rare Earth Elements** (REE) can be found in electronic equipment also in very small concentrations compared to the base metals. The REE fulfill versatile functions and can be found in batteries, flat display panels, and various components from the PCBs. Also, their physical form varies significantly, so they can be found in alloys with other metals, as thin layers, or as homogenous material. Although it is possible to detect and quantify the REE by ICP analytical techniques, the most efficient method for the analysis of REE still needs to be verified. Since the REE closely associated with the development of semiconductor materials, it would be most advantageous if the analytical procedure could encompass both the REE and semiconductors simultaneously.

6. Conclusion

After analysing the results of the conducted analytical tests, it can be deduced that in the established time periods for analysed samples much higher influence on the material composition trends have the cost-effectiveness measures, e.g. thinner magnets, and smaller components, than a technological development, e.g. data storing efficiency, development of integrated circuits, and development of read/write heads.

In conclusion, by organising the complex components according to the year of manufacture and considering them as sum of their parts, rather than just focusing on the total material composition of a particular component, it is possible to portray changes of trends in material composition over time and to pinpoint these changes in to a specific part of the complex component. This approach creates reliable structure in the otherwise variable material composition of the complex components.

The following points have emerged from the present work for further research. First, after application of simple material identification tests, it became obvious that a more comprehensive method or set of tests for differentiation of yellow/red metals in WEEE, i.e. bronze, brass, and copper, would increase the overall efficiency of the proposed material composition analysis. Second, the need for standardization and adjustment of ICP analyses exclusively for WEEE is apparent. For this reason, it would be highly beneficial to develop a set of standards for the analysis of different kinds of WEEE with regard to the mechanical sample preparation, digestions methods in accordance with a specific aim of the analysis, and certified reference materials (CRMs) adapted for WEEE samples.

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ANNEX I – In depth disassembly

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-1	HD-2	HD-3	HD-4	HD-5	HD-6
1	Cover assembly	Top casing	Ferrous metal	89.9	114.2	128.6	113.0	99.0	72.3
2	Cover assembly	Base casing	Cast aluminium	237.0	230.5	236.9	236.2	240.7	201.2
3	PCB	PCB	Assembly	23.0	18.9	29.0	22.7	26.5	36.4
4	Disk stack assembly	Platter(s)	Metal	31.2	62.6	45.7	62.8	68.4	28.7
5	Voice coil assembly	Retainer	Ferrous metal	15.8	19.6	19.3	19.7	27.5	22.8
5	Voice coil assembly	Magnet	NdFeB	4.3	10.0	7.5	10.4	5.7	N/E
6	Voice coil assembly	Retainer	Ferrous metal	19.7	32.7	23.9	32.4	29.4	21.0
6	Voice coil assembly	Magnet	NdFeB	3.8	10.2	7.5	10.4	5.8	15.1
7	Mechanics	Screws	Ferrous metal	7.0	8.3	5.2	6.9	6.4	3.3
8	Voice coil assembly	Read / write premplifier	Aluminium	0.1	0.8	0.5	0.2	0.2	0.3
9	Voice coil assembly	Read / write premplifier	Assembly	1.1	1.8	3.1	3.2	2.8	3.5
10	Cable	Ribbon cable	Cu, plastics	0.1	0.8	0.4	0.1	0.1	0.1
12	Mechanics	Machanical components	Plastics	3.1	10.5	3.3	1.5	5.7	4.3
13	Spindle assembly	Coil	Cu, ferrous metal	6.3	6.0	8.3	5.6	8.1	6.4
14	Disk stack assembly	Spacer	Aluminium	3.8	4.1	2.0	3.8	4.1	7.4
15	Actuator arm	Voice coil	Cu	0.7	2.0	2.1	1.0	1.0	1.6
15	Actuator arm	Voice coil	Plastics	0.3	0.8	0.9	4.0	0.5	0.7
16	Spindle assembly	Spindle retainer	Aluminium	13.2	15.3	16.9	15.7	16.5	16.5
16	Spindle assembly	Spindle magnet	NdFeB	2.3	2.2	3.0	2.3	2.3	2.3
17	Spindle assembly	DC Motor	Assembly	13.7	12.9	14.2	12.5	9.5	13.2
18	Disk stack assembly	Spindle cover	Aluminium	2.5	3.3	4.0	3.1	4.2	3.0
19	Actuator arm	Acutator arm	Aluminium	4.3	8.7	16.2	7.6	7.6	9.8
20	Actuator arm	Slider head + suspension	Metal	0.0	0.1	0.2	0.5	0.5	0.2
22	Actuator axis	DC Motor	Assembly	8.0	7.9	N/E	8.2	4.0	8.0
24	Mechanics	Pad insulator	Plastics	N/E	0.5	0.7	1.2	0.9	0.1

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-8	HD-9	HD-10	HD-11	HD-12	HD-13
1	Cover assembly	Top casing	Ferrous metal	111.7	72.2	136.5	87.2	105.0	121.8
2	Cover assembly	Base casing	Cast aluminium	260.6	270.4	244.4	250.1	269.0	275.8
3	PCB	PCB	Assembly	26.1	34.6	33.4	26.7	25.8	21.3
4	Disk stack assembly	Platter(s)	Metal	91.7	14.4	17.3	68.3	45.8	45.6
5	Voice coil assembly	Retainer	Ferrous metal	24.5	22.2	61.2	29.2	13.4	30.9
5	Voice coil assembly	Magnet	NdFeB	11.1	15.3	15.7	5.3	4.3	9.9
6	Voice coil assembly	Retainer	Ferrous metal	28.2	22.0	73.4	27.5	11.9	24.1
6	Voice coil assembly	Magnet	NdFeB	11.1	N/E	11.3	2.9	4.6	10.2
7	Mechanics	Screws	Ferrous metal	13.2	7.3	8.1	7.2	8.7	9.9
8	Voice coil assembly	Read / write premplifier	Aluminium	0.3	0.4	0.3	0.1	N/E	0.2
9	Voice coil assembly	Read / write premplifier	Assembly	1.3	3.5	4.6	1.2	4.6	3.6
10	Cable	Ribbon cable	Cu, plastics	0.4	0.1	0.1	0.1	0.1	0.1
12	Mechanics	Machanical components	Plastics	5.2	2.6	10.4	7.3	1.9	1.3
13	Spindle assembly	Coil	Cu, ferrous metal	5.9	6.9	8.5	7.6	6.2	5.5
14	Disk stack assembly	Spacer	Aluminium	7.2	2.8	2.8	4.1	1.0	3.1
15	Actuator arm	Voice coil	Cu	3.7	0.6	1.2	0.5	1.2	3.1
15	Actuator arm	Voice coil	Plastics	N/E	1.9	N/E	2.9	1.7	0.3
16	Spindle assembly	Spindle retainer	Aluminium	19.1	12.3	15.1	16.1	15.3	13.5
16	Spindle assembly	Spindle magnet	NdFeB	3.1	2.0	2.3	2.8	2.8	3.9
17	Spindle assembly	DC Motor	Assembly	12.7	8.6	12.7	6.3	13.9	12.3
18	Disk stack assembly	Spindle cover	Aluminium	5.1	2.3	3.2	4.3	1.7	4.0
19	Actuator arm	Acutator arm	Aluminium	10.0	10.9	7.9	5.5	5.9	9.8
20	Actuator arm	Slider head + suspension	Metal	0.1	0.1	0.3	0.1	0.1	0.2
22	Actuator axis	DC Motor	Assembly	9.5	2.9	6.4	7.9	8.1	7.8
24	Mechanics	Pad insulator	Plastics	0.8	52.7	1.4	1.2	0.9	1.0

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-14	HD-15	HD-16	HD-17	HD-18	HD-19
1	Cover assembly	Top casing	Ferrous metal	115.3	103.2	116.0	131.1	105.8	186.7
2	Cover assembly	Base casing	Cast aluminium	246.5	271.6	247.0	248.5	280.0	230.6
3	PCB	PCB	Assembly	32.8	25.6	25.4	36.1	25.5	31.9
4	Disk stack assembly	Platter(s)	Metal	68.5	22.7	68.5	68.8	45.7	22.6
5	Voice coil assembly	Retainer	Ferrous metal	28.7	13.5	29.2	24.6	11.6	23.5
5	Voice coil assembly	Magnet	NdFeB	5.6	3.7	5.6	6.9	4.4	7.4
6	Voice coil assembly	Retainer	Ferrous metal	26.8	11.9	27.2	19.3	13.6	25.5
6	Voice coil assembly	Magnet	NdFeB	5.1	4.5	5.6	7.0	4.4	7.4
7	Mechanics	Screws	Ferrous metal	6.8	8.5	6.7	4.2	8.7	9.1
8	Voice coil assembly	Read / write premplifier	Aluminium	0.1	1.0	0.1	0.4	0.3	0.3
9	Voice coil assembly	Read / write premplifier	Assembly	2.9	5.2	2.9	3.3	4.2	3.4
10	Cable	Ribbon cable	Cu, plastics	0.1	0.1	0.1	0.1	0.1	0.2
12	Mechanics	Machanical components	Plastics	5.8	3.7	6.2	3.0	3.4	0.1
13	Spindle assembly	Coil	Cu, ferrous metal	7.9	7.3	7.6	7.4	6.2	5.7
14	Disk stack assembly	Spacer	Aluminium	3.8	2.7	4.2	4.0	1.1	3.4
15	Actuator arm	Voice coil	Cu	0.6	1.2	0.4	1.4	0.9	1.3
15	Actuator arm	Voice coil	Plastics	1.9	N/E	2.5	0.9	1.6	2.0
16	Spindle assembly	Spindle retainer	Aluminium	30.5	16.7	16.3	15.6	15.1	15.1
16	Spindle assembly	Spindle magnet	NdFeB	2.8	2.1	2.8	3.2	2.8	2.6
17	Spindle assembly	DC Motor	Assembly	N/E	13.8	13.7	13.9	13.7	12.3
18	Disk stack assembly	Spindle cover	Aluminium	3.8	1.5	3.8	1.6	1.6	1.5
19	Actuator arm	Acutator arm	Aluminium	6.1	1.6	5.1	7.3	5.9	5.9
20	Actuator arm	Slider head + suspension	Metal	0.1	0.0	0.2	0.2	0.1	0.2
22	Actuator axis	DC Motor	Assembly	3.7	8.4	4.1	8.2	7.5	4.8
24	Mechanics	Pad insulator	Plastics	1.6	0.9	0.7	0.9	1.0	1.6

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-20	HD-21	HD-22	HD-23	HD-24	HD-25
1	Cover assembly	Top casing	Ferrous metal	90.6	117.9	106.2	95.2	116.4	97.1
2	Cover assembly	Base casing	Cast aluminium	280.0	234.0	276.1	245.5	256.2	235.9
3	PCB	PCB	Assembly	22.0	19.8	27.2	21.2	29.6	31.0
4	Disk stack assembly	Platter(s)	Metal	45.9	62.6	46.2	31.3	28.5	23.0
5	Voice coil assembly	Retainer	Ferrous metal	32.2	33.1	13.3	8.5	29.3	23.1
5	Voice coil assembly	Magnet	NdFeB	6.6	10.1	4.4	2.5	8.5	4.0
6	Voice coil assembly	Retainer	Ferrous metal	27.4	19.9	11.5	10.3	21.5	21.2
6	Voice coil assembly	Magnet	NdFeB	6.2	9.9	4.4	2.8	8.3	4.1
7	Mechanics	Screws	Ferrous metal	7.9	8.4	8.8	8.8	9.5	3.6
8	Voice coil assembly	Read / write premplifier	Aluminium	0.6	0.3	0.1	0.1	0.5	0.4
9	Voice coil assembly	Read / write premplifier	Assembly	2.0	3.5	4.8	4.3	3.6	4.2
10	Cable	Ribbon cable	Cu, plastics	0.6	0.4	0.1	0.1	0.1	0.1
12	Mechanics	Machanical components	Plastics	2.1	8.7	5.3	0.2	3.4	2.7
13	Spindle assembly	Coil	Cu, ferrous metal	5.6	5.6	6.4	7.0	5.7	8.5
14	Disk stack assembly	Spacer	Aluminium	0.8	3.9	1.4	N/E	5.1	N/E
15	Actuator arm	Voice coil	Cu	1.8	2.3	1.2	0.8	1.4	1.0
15	Actuator arm	Voice coil	Plastics	N/E	N/E	1.8	1.2	3.7	N/E
16	Spindle assembly	Spindle retainer	Aluminium	14.5	13.5	14.7	12.9	17.5	20.9
16	Spindle assembly	Spindle magnet	NdFeB	2.4	4.8	2.8	2.8	2.1	2.6
17	Spindle assembly	DC Motor	Assembly	13.2	12.7	15.6	8.0	7.7	14.0
18	Disk stack assembly	Spindle cover	Aluminium	3.7	3.1	2.1	2.3	2.7	4.0
19	Actuator arm	Acutator arm	Aluminium	6.8	9.7	5.6	3.1	8.1	7.3
20	Actuator arm	Slider head + suspension	Metal	0.2	0.2	0.1	0.1	0.1	0.1
22	Actuator axis	DC Motor	Assembly	8.1	7.8	8.3	7.0	5.7	8.3
24	Mechanics	Pad insulator	Plastics	0.8	0.7	1.0	0.6	4.1	0.6

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-26	HD-27	HD-28	HD-29
1	Cover assembly	Top casing	Ferrous metal	94.4	107.0	91.5	190.5
2	Cover assembly	Base casing	Cast aluminium	207.4	280.0	226.9	215.2
3	PCB	PCB	Assembly	17.0	26.8	25.0	21.8
4	Disk stack assembly	Platter(s)	Metal	30.9	45.6	22.6	22.6
5	Voice coil assembly	Retainer	Ferrous metal	8.6	13.6	13.7	19.1
5	Voice coil assembly	Magnet	NdFeB	1.3	4.4	3.0	3.0
6	Voice coil assembly	Retainer	Ferrous metal	7.5	12.2	10.7	16.0
6	Voice coil assembly	Magnet	NdFeB	1.6	4.5	3.4	3.5
7	Mechanics	Screws	Ferrous metal	4.2	8.8	7.1	4.0
8	Voice coil assembly	Read / write premplifier	Aluminium	0.1	0.5	0.1	0.1
9	Voice coil assembly	Read / write premplifier	Assembly	2.0	4.4	2.8	2.9
10	Cable	Ribbon cable	Cu, plastics	0.1	0.1	0.1	0.1
12	Mechanics	Machanical components	Plastics	0.9	3.1	1.9	0.9
13	Spindle assembly	Coil	Cu, ferrous metal	5.7	6.8	7.5	5.8
14	Disk stack assembly	Spacer	Aluminium	N/E	1.4	N/E	N/E
15	Actuator arm	Voice coil	Cu	1.7	1.6	0.5	0.5
15	Actuator arm	Voice coil	Plastics	N/E	2.0	1.4	1.4
16	Spindle assembly	Spindle retainer	Aluminium	13.4	15.3	15.1	12.2
16	Spindle assembly	Spindle magnet	NdFeB	2.4	2.8	2.8	2.5
17	Spindle assembly	DC Motor	Assembly	4.7	13.8	6.6	13.7
18	Disk stack assembly	Spindle cover	Aluminium	2.8	2.3	4.5	4.1
19	Actuator arm	Acutator arm	Aluminium	4.3	5.9	3.0	2.8
20	Actuator arm	Slider head + suspension	Metal	0.1	0.2	0.1	0.1
22	Actuator axis	DC Motor	Assembly	6.2	7.7	6.1	6.1
24	Mechanics	Pad insulator	Plastics	N/E	0.6	1.2	0.8

Hard Disk Drives

Comp. no.	Component Lvl 1	Component Lvl 2	Material [in g]	HD-30	HD-31	HD-32
1	Cover assembly	Top casing	Ferrous metal	93.8	183.1	104.0
2	Cover assembly	Base casing	Cast aluminium	209.5	217.5	277.9
3	PCB	PCB	Assembly	17.5	24.1	26.2
4	Disk stack assembly	Platter(s)	Metal	31.4	22.3	45.7
5	Voice coil assembly	Retainer	Ferrous metal	9.0	19.6	13.6
5	Voice coil assembly	Magnet	NdFeB	1.7	3.5	4.3
6	Voice coil assembly	Retainer	Ferrous metal	7.4	16.4	11.7
6	Voice coil assembly	Magnet	NdFeB	1.3	3.6	4.4
7	Mechanics	Screws	Ferrous metal	4.7	4.2	9.2
8	Voice coil assembly	Read / write premplifier	Aluminium	0.1	0.1	0.1
9	Voice coil assembly	Read / write premplifier	Assembly	1.6	2.2	4.5
10	Cable	Ribbon cable	Cu, plastics	0.1	0.1	0.1
12	Mechanics	Machanical components	Plastics	0.5	N/E	3.8
13	Spindle assembly	Coil	Cu, ferrous metal	5.5	6.0	6.9
14	Disk stack assembly	Spacer	Aluminium	N/E	N/E	1.2
15	Actuator arm	Voice coil	Cu	1.6	1.9	1.1
15	Actuator arm	Voice coil	Plastics	N/E	N/E	1.6
16	Spindle assembly	Spindle retainer	Aluminium	13.0	11.2	15.8
16	Spindle assembly	Spindle magnet	NdFeB	2.5	2.5	2.8
17	Spindle assembly	DC Motor	Assembly	4.6	11.5	14.8
18	Disk stack assembly	Spindle cover	Aluminium	1.9	2.2	1.3
19	Actuator arm	Acutator arm	Aluminium	4.3	4.2	5.5
20	Actuator arm	Slider head + suspension	Metal	0.1	0.1	0.1
22	Actuator axis	DC Motor	Assembly	6.1	6.0	8.5
24	Mechanics	Pad insulator	Plastics	N/E	N/E	1.0

Optical Disc Drives

Components [in g]	Material	Compt. no.	CD-ROM-1	CD-ROM-2	CD-ROM-4	CD-ROM-6	CD-ROM-7
Ferrous metal parts	Ferrous metal	1	394.9	597.6	395.5	619.6	731.6
Plastic parts	Plastics	2	151.1	166.8	165.6	164.7	185.6
PCB	Q2	3	71.6	70.2	70.9	91.0	103.5
PCB	Q3	4	N/E	12.1	N/E	N/E	1.7
Micro stepping motor	Assembly	5	17.0	15.1	16.9	17.4	26.1
DC Motor	Assembly	6	36.0	29.7	36.2	41.5	55.5
DC Motor	Assembly	7	20.7	20.0	20.8	19.8	20.2
Laser assembly	Assembly	8	29.1	36.9	23.5	24.9	17.7
Ribbon cable	Cu, plastics	9	1.0	3.9	1.8	2.4	2.7

Components [in g]	Material	Compt. no.	CD-ROM-9	CD-ROM-10	CD-ROM-11	CD-ROM-12	CD-ROM-13
Ferrous metal parts	Ferrous metal	1	416.2	458.2	438.6	633.8	408.1
Plastics parts	Plastics	2	155.8	246.2	201.5	152.0	200.4
PCB	Q2	3	53.4	87.7	60.9	51.0	63.4
PCB	Q3	4	5.5	14.4	9.4	6.4	12.1
Micro stepping motor	Assembly	5	16.1	20.4	21.4	19.7	15.1
DC Motor	Assembly	6	37.8	31.4	31.0	40.1	34.8
DC Motor	Assembly	7	20.9	18.3	24.8	19.9	20.7
Laser assembly	Assembly	8	35.7	15.9	25.7	12.1	19.8
Ribbon cable	Cu, plastics	9	1.1	4.3	5.9	2.6	3.9

Optical Disc Drives

Components [in g]	Material	Compt. no.	CD-ROM-14	CD-ROM-15	CD-ROM-16	CD-ROM-17	CD-ROM-18
Ferrous metal parts	Ferrous metal	1	558.1	356.5	375.9	413.6	370.2
Plastic parts	Plastics	2	184.0	152.0	153.0	157.7	155.0
PCB	Q2	3	46.3	46.8	29.2	45.9	47.7
PCB	Q3	4	10.6	4.8	4.7	5.8	9.0
Micro stepping motor	Assembly	5	17.0	16.3	15.7	16.5	16.7
DC Motor	Assembly	6	34.7	35.1	41.0	37.8	39.1
DC Motor	Assembly	7	19.3	20.6	20.5	20.4	20.3
Laser assembly	Assembly	8	17.5	34.6	34.3	40.0	23.2
Ribbon cable	Cu, plastics	9	1.3	0.6	1.0	1.2	1.4

Power Supply Unit from PC

Component Lvl 1	Component Lvl 2	Component no.	Material [in g]	Netzteil-PC-1	Netzteil-PC-2	Netzteil-PC-3	Netzteil-PC-4	Netzteil-PC-5
Casing1	Casing	1	Ferrous metal	274.3	279.6	312.4	199.3	237.4
Casing2	Casing	2	Ferrous metal	273.6	244.4	254.4	209.3	213.4
Cables	Ribbon cable	3	Cu, plastic	285.0	309.0	201.5	159.6	222.8
PCB	PCB	4	Assembly	387.0	450.9	493.4	289.8	401.3
Capacitor	Radial style capacitor	5	Assembly	22.5	27.0	8.4	17.0	N/E
Mechanics	Screws	6	Ferrous metal	13.9	15.9	19.1	11.9	18.5
Plug	Plug	7	Assembly	10.8	11.2	8.4	11.0	14.4
Plug	Plug	8	Assembly	15.0	N/E	N/E	N/E	N/E
Mechanics	Holders	9	Plastics	0.3	0.3	3.1	4.6	0.05
Heatsink 1	Heatsink	10	Aluminium	25.1	39.9	65.3	27.2	55.1
Heatsink 1	Holders	10	Ferrous metal	0.6	0.6	N/E	0.4	0.5
Heatsink 2	Heatsink	11	Aluminium	44.0	38.7	47.3	31.1	54.9
Heatsink2	Holders	11	Ferrous metal	0.6	0.6	1.7	11.4	0.8
Fan	Magnet	12	Magnet	5.5	10.2	10.6	5.4	6
Fan	Propeller	12	Plastics, ferrous metals	18.3	31.1	27.6	16.2	13.4
Fan	DC motor	12	Assembly	3.8	4.4	3.1	3.1	3.8
Fan	Housing	13	Plastics	29.0	52.3	63.1	21.7	28
Fan	Cable	14	Cu, plastic	0.3	0.1	0.4	0.4	0.1
Fan	PCB	15	Assembly	1.2	0.8	1.9	1.5	1.8
Fan	Coil	16	Cu, ferrous metal	9.3	14.1	14.3	9.1	15.8
Fan	Sticker	17	Plastics	0.1	0.1	N/E	0.1	0.05
Mechanics	Bumper	18	Ferrous metal	N/E	38.7	N/E	N/E	N/E
Transformer	Transformer	19	Assembly	N/E	332.8	422.3	N/E	414.9
Switch	Switch	20	Assembly	4.5	3.2	3.0	10.3	20.1
Mechanics	Foil	21	Plastics	3.7	8.1	5.9	4.2	6
				1428.3	1914.0	1967.2	1044.5	1729.1

Power Supply Unit from PC

Component Lvl 1	Component Lvl 2	Component no.	Material [in g]	Netzteil-PC-6	Netzteil-PC-7	Netzteil-PC-8	Netzteil-PC-9	Netzteil-PC-10
Casing1	Casing	1	Ferrous metal	206.3	200.4	175.0	199.9	267.2
Casing2	Casing	2	Ferrous metal	193.2	191.3	175.1	199.2	253.6
Cables	Ribbon cable	3	Cu, plastic	261.9	138.2	222.5	198.3	304.6
PCB	PCB	4	Assembly	381.7	263.5	290.1	203.3	387.7
Capacitor	Radial style capacitor	5	Assembly	35.7	5.1	12.2	N/E	4.2
Mechanics	Screws	6	Ferrous metal	16.0	13.2	11.9	11.2	17.4
Plug	Plug	7	Assembly	10.9	N/E	10.7	0.5	11.1
Plug	Plug	8	Assembly	N/E	10.9	10.0	8.2	N/E
Mechanics	Holders	9	Plastics	0.5	3.8	3.7	4.4	0.5
Heatsink 1	Heatsink	10	Aluminium	34.2	21.4	30.7	22.3	46.3
Heatsink 1	Holders	10	Ferrous metal	0.4	0.3	0.7	0.3	2.1
Heatsink 2	Heatsink	11	Aluminium	51.7	14.7	42.7	17.0	71.2
Heatsink2	Holders	11	Ferrous metal	0.3	0.3	0.4	0.5	1.8
Fan	Magnet	12	Magnet	5.3	5.3	5.1	5.2	6.4
Fan	Propeller	12	Plastics, ferrous metals	16.7	12.7	13.3	14.1	12.7
Fan	DC motor	12	Assembly	3.1	2.2	2.6	2.3	2.7
Fan	Housing	13	Plastics	34.3	18.9	39.4	25.9	31.4
Fan	Cable	14	Cu, plastic	0.3	0.4	0.1	0.1	0.3
Fan	PCB	15	Assembly	2.1	0.6	1.6	0.5	0.8
Fan	Coil	16	Cu, ferrous metal	10.6	6.8	9.6	8.3	10.2
Fan	Sticker	17	Plastics	0.1	N/E	0.0	0.1	0.1
Mechanics	Bumper	18	Ferrous metal	9.8	22.0	N/E	N/E	N/E
Transformer	Transformer	19	Assembly	N/E	238.7	N/E	215.4	417.8
Switch	Switch	20	Assembly	3.5	3.4	3.2	4.3	N/E
Mechanics	Foil	21	Plastics	5.7	N/E	N/E	4.3	5.7
				1284.3	1174.1	1060.6	1145.6	1855.8

Active fan

Comp. no.	Component	Material [in g]	Fan-PC-1	Fan-PC-2	Fan-PC-3	Fan-PC-4	Fan-PC-5
12	El. Motor	Magnet	5.5	5.1	5.1	10.6	5.4
12	El. Motor	Ferrous metal	4.1	3.9	3.9	5.4	4.1
12	Propeller	Plastics	14.2	10.8	11.4	22.0	12.1
12	El. Motor	Cu, ferrous metal	3.8	2.4	2.0	3.1	3.1
13	Housing	Plastics	29.0	27.3	27.0	63.1	21.7
14	Cable	Cu, plastic	0.3	0.1	0.1	0.4	0.4
15	PCB	Assembly	1.2	0.4	0.4	1.9	1.5
16	El. Motor	Cu, ferrous metal	9.3	6.9	7.2	14.3	9.1
17	Sticker	Plastics	0.1	0.1	0.1	N/E	0.1

Comp. no.	Component	Material [in g]	Fan-PC-6	Fan-PC-7	Fan-PC-8	Fan-PC-9	Fan-PC-10	Fan-PC-11
12	El. Motor	Magnet	6.0	5.3	5.3	5.1	5.2	6.4
12	El. Motor	Ferrous metal	4.1	4.0	4.0	3.9	2.3	2.7
12	Propeller	Plastics	9.3	12.7	8.7	9.4	10.6	9.1
12	El. Motor	Cu, ferrous metal	3.8	3.1	2.2	2.6	3.5	3.7
13	Housing	Plastics	28.3	34.3	18.9	39.4	25.9	31.4
14	Cable	Cu, plastic	0.1	0.3	0.4	0.2	0.1	0.3
15	PCB	Assembly	1.8	2.1	0.6	1.6	0.5	0.8
16	El. Motor	Cu, ferrous metal	15.8	10.6	6.8	9.6	8.3	10.2
17	Sticker	Plastics	0.1	0.1	N/E	0.1	0.1	0.1

Power Supply Units from Printers

Model	Component no.	Material	Mass [g]	Remarks
Netzteil-1	Housing	Plastics	77.7	PPE+PS-FE(40)
Netzteil-1	PCB	PCBs - Q3	100	
Netzteil-1	Screws	Ferrous metal	1.3	
Netzteil-2	Housing	Plastics	50.3	PPE+PS-FE(40)
Netzteil-2	PCB	PCBs - Q3	83	
Netzteil-2	Screws	Ferrous metal	1.7	
Netzteil-3	Housing	Plastics	114	PPE+PS-FE(40)
Netzteil-3	PCB	PCBs - Q3	202	
Netzteil-3	Screws	Ferrous metal	1.8	
Netzteil-4	Housing	Plastics	97.6	PPE+PS-FE(40)
Netzteil-4	PCB	PCBs - Q3	135	
Netzteil-4	Screws	Ferrous metal	1.4	
Netzteil-5	Housing	Plastics	50.6	PPE+PS-FE(40)
Netzteil-5	PCB	PCBs - Q3	94	
Netzteil-5	Screws	Ferrous metal	1.4	
Netzteil-6	Housing	Plastics	41.9	PPE+PS-FE(40)
Netzteil-6	PCB	PCBs - Q3	79	
Netzteil-6	Screws	Ferrous metal	1.1	
Netzteil-7	Housing	Plastics	84.2	PPE+PS-FE(40)
Netzteil-7	PCB	PCBs - Q3	123	
Netzteil-7	Screws	Ferrous metal	1.8	
Netzteil-8	Housing	Plastics	50.8	PPE+PS-FE(40)
Netzteil-8	PCB	PCBs - Q3	96	
Netzteil-8	Screws	Ferrous metal	1.2	
Netzteil-9	Housing	Plastics	50.6	PPE+PS-FE(40)
Netzteil-9	PCB	PCBs - Q3	97	
Netzteil-9	Screws	Ferrous metal	1.4	
Netzteil-10	Housing	Plastics	34.9	FR-2K
Netzteil-10	PCB	PCBs - Q3	82	
Netzteil-10	Screws	Ferrous metal	1.1	

ANNEX II – ICP-OES Calibration curves