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Computational Model for the improved management of E-waste

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I hereby declare that the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Abstract

This dissertation investigates critical challenges in the field of sustainable electronic waste (e-waste) management, with a particular focus on the fragmentation of knowledge across technological, material, and hazard domains, and the widespread reliance on generalized assumptions in material recovery processes. To address these issues, this research has investigated the possibility of developing a multi-domain ontology-based Decision Support System (DSS). The system is scalable, reusable, and can be integrated to support informed decision-making aligned with green circular economy principles.

The developed ontology consolidates key knowledge by integrating information derived from scientific literature and industry practices, while keeping in mind the European Union legislative frameworks, particularly the Waste from Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) directives. As a result, a proof of concept was initially established with a focus on the solar photovoltaic (PV) sector, to demonstrate the model's, flexibility, and capacity for expansion without compromising its foundational structure. To validate the ontology's scalability and broader applicability, some concepts from the printed circuit boards (PCBs) sector were incorporated.

Additionally, a comprehensive experimental study was conducted on different PCB categories extracted from personal computers, including motherboards, RAM modules, and CPUs/chipsets. This in-depth investigation has permitted to assess the variations in material compositions across categories and models, with particular attention to critical and valuable metals such as copper, gold, and silver. The results revealed significant differences within PCB categories. This underlined the importance of using precise, category-specific data in WEEE handling and highlighting the potential of the developed ontology to tackle this issue by capturing the variability through detailed and flexible data structures.

In parallel, experimental investigations were carried out to evaluate the effect of Dimethyl sulfoxide (DMSO) solvent pre-treatment on the recovery efficiency of metals from PCB samples. Different particle size groups were analysed to determine their influence on the liberation and extraction of metals, particularly copper. The results were promising allowing to reach an optimised DMSO pre-treatment applied to PCBs of particle size range between 5.6 mm to 2 mm, leading to a significant improvement in the metal recovery rates. The investigation also

showed that a near-complete recovery was achieved without pre-treatment for particles smaller than 400 μm, highlighting a trade-off between process complexity and material recovery optimization.
The developed ontology was validated using SPARQL queries which allowed to imitate a fully developed system. The validation process ensured the logical consistency, internal coherence, and responsiveness of the system to the different decision-making scenarios. Additionally, the dissertation gives a critical overview of the limitations encountered, including data quality challenges, integration complexity, and the need for dynamic updating mechanisms. Solutions are proposed to address these issues and to enable future expansions of the system. Collaboration Eni SpA as an industrial partner has ensured the practical relevance and multidisciplinary robustness of the developed solution.
In conclusion, this research delivers a comprehensive, ontology-driven decision support system that not only bridges interdisciplinary gaps in WEEE management but also couples modelling with experimental validation through PCB material characterization and DMSO solvent pre-treatment for metal recovery optimization. The DSS framework developed offers a powerful tool for sustainable WEEE management which is adaptable to different contexts and capable of supporting the evolving recovery strategies and techniques. It establishes a solid foundation for future research directions in the field of computational sustainability with the goal of integrating technical, environmental, economic, and social dimensions into circular economy practices and offer a simplified overview of the WEEE sector and its sound handling practices.

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Acronyms and abbreviations

AI	Artificial intelligence
BFR	Brominated Flame Retardants
CEAP	Circular economy action plan
CPU	Central Processing Unit
CRM	Critical Raw Material
DMA	Dimethylacetamide
DMF	Dimethylformamide
DMSO	Dimethyl sulfoxide
DSS	Decision Support System
EBS	Ethylene Bis(stearamide)
EEE	Electrical and Electronic Equipment
E-waste	Electronic waste
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
EVA	Ethyl vinyl acetate
GUI	Graphical User Interface
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
Kg	kilograms
LCA	Life Cycle Assessment
Mt	Million tonnes
NMP	N-methyl-2-pyrrolidone
PACE	Partnership for Action on Computing Equipment
PACE II	Partnership for Action on Challenges relating to WEEE
PBDE	Polybromodiphenylethers
PC	Personal computer
PCB	Printed circuit board
POC	Proof of concept
POP	Persistent Organic Pollutant
PPE	Personal Protection Equipment
RAM	Random Access Memory
SDGs	Sustainable Development Goals
Solar PVs	Solar Photovoltaics
TBBPA	Tetrabromobisphenol A
UN	United Nations
USD	United States Dollars
WEEE	Waste Electrical and Electronic Equipment
XRF	X-ray fluorescence spectroscopy

Chapter 1

Introduction

In 1992, the United Nations (UN) Conference on Environment and Development defined a strategy in an attempt to conceptualise the idea of sustainable development and encourage a shift towards it [1]. Fast forward to the year 2015, the 2030 agenda for sustainable development defined the UN Sustainable Development Goals (SDGs) [2]. The agenda has thematic goals related to energy, climate, urbanization, science and other aspects of life. Among these goals are the 9th goal which is related to industry and innovation, and the 12th goal which aspires to reach responsible consumption and production [2]. The achievement of the 9th goal is directly hindering the 12th goal related to consumption patterns and responsible waste handling.

In recent years, electronics and electrical equipment have been continuously evolving. This evolution is driven by the advancement in manufacturing technologies and the groundbreaking improvements in the field of microchips and processing power which allow for cost reductions [3]. It has also encouraged the continuous update of electronic devices triggering an unsustainable consumption pattern and giving rise to the problem of e-waste [4].

1.1. WEEE

WEEE covers discarded products that contain electrical components and are powered by electricity or a power source [5]. These devices are discarded at their end of life whether because they are malfunctioning or they are outdated and no longer support technological advancement. Given the definition of WEEE, it embodies a far-reaching scope of devices and products. These devices can be as small as a personal smartwatch, mobile phones and headphones, medium sizes such as computers and household appliances, or large sizes such as refrigerators and washing machines. The categorization of these products varies slightly from one governing body to another. For instance, the E-waste Statistics Guidelines on Classification Reporting and Indicators has catalogued WEEE into six main groups: Temperature exchange equipment, Screens and monitors, Lamps, Large equipment, small equipment, and Telecommunication equipment [6]. The European Union (EU) Waste Electrical and Electronic Equipment (WEEE) Directive classified WEEE into ten different groups: large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment and photovoltaic panels, lighting equipment, electrical and electronic tools, toys, leisure and sports equipment, medical devices, monitoring and control instruments, and automatic dispensers [5]. Not to confuse are some electronic equipment and devices which satisfy the definition of WEEE but do not fall under the WEEE umbrella; this includes filament bulbs, batteries, military equipment, industrial tools, space waste, medical devices, devices installed as part of other equipment and equipment produced for research purposes [5], [6]. These exclusions are sometimes covered by other legislative bodies such as the Battery Directive in the EU that deals with batteries and accumulators [7].

Between 2010 and 2022 the amount of WEEE generated has increased from 34 billion kilograms (kg) to an astounding 62 billion kg. Concurrently, only 13.8 billion kg were collected and handled formally leaving almost 80% of the WEEE generated without proper handling [6].

The amount of WEEE is expected to continue rising. Experts estimate that by the year 2030, the WEEE generated from solar photovoltaics (solar PVs) only will reach 2.4 billion kg, a fourfold increase from the year 2022 [6]. This is due to the current expansion in the green energy sector. Between the years 2019 and 2049, the expansion in solar PV usage is expected to reach tenfold generating waste that can reach up to 78 billion kg by the year 2050 [8], [9].

An in-depth analysis of the WEEE problem suggests that the continuous increase is a two-fold problem. Firstly, the increasing penetration and reliability of electronics and electric devices into our everyday lives, and secondly the constant advancement in technology which entails the upgrading of owned electric devices and has resulted in shortening the life cycle of electronics. A correlation is also found between the generation of WEEE and the GDP of countries; in which countries with higher GDP generated larger amounts of WEEE due to the increased purchasing power of its inhabitants [6], [10], [11].

Adding to the complexity of WEEE is the number of materials it contains reaching over one thousand different materials some being hazardous, non-degradable or ozone-depleting [12]. In addition, many of the metals comprising WEEE are heavy metals, precious or rare earth metals; these metals are usually found mixed with persistent organic pollutants (POP), plastics, and glass [10], [13], [14].

Regarding plastics, which can represent between 2.8%-72.3% of the WEEE making it cost effective to recycle, it was categorized in recent studies into brominated and non-brominated plastics with non-brominated plastics occurring more than double the mass of brominated plastics in WEEE and mainly black Electrical and Electronic Equipment (EEE) products contained the brominated polymers. However, more than 15 types of polymers can be found in WEEE [12].

In 2022, the WEEE generated was made up of 50% metals, of which 61% is iron, almost 27% plastics and 22% composite materials and glass. The calculated value of only the metal part of the generated WEEE is about 91 billion USD, of which currently only 28 billion USD is being recovered saving the environment 900 billion kg of ore that would alternatively be necessary to produce [6]. One study estimates a staggering 452 billion USD in recoverable materials from solar PV-related waste produced only in India between 2020 and 2047, this is based on an expected waste generation of 295 billion kg during the same period [15].

The richness of WEEE with a myriad of materials has made it a double-edged sword; it has driven more interest in the recovery of some of the materials they contain, especially materials with high economic value such as metals, triggering what is known as urban mining. Urban mining is the use of waste to extract resources instead of natural ores from the earth's crust [6]. It reduces the energy needed for new material production as well as the waste associated with the production of new materials. In polymers, it was found that recycling would help conserve 80% of the energy needed compared to that needed for newly produced materials [12]. However, the prioritization of handling these materials and retrieving them from the WEEE is usually driven by economic incentives rather than environmental and social ones.

Moreover, the richness of materials, many of which are hazardous or non-degradable, has stressed the need for the development of WEEE handling schemes globally. Most developed countries have WEEE handling regulations in place except for New Zealand which mainly landfills the WEEE produced. The implemented regulations usually included Extended Producer Responsibility (EPR) schemes which hold accountable the producers, importers, or sellers of electronics for their products put on the market at their end-of-lifecycle, implemented for instance in Taiwan, Canada, and the EU. Some of the regulations also adopt the 3Rs, Reduce, Reuse and Recycle, such as in South Africa and Japan. The review shows that also developing countries have started to implement WEEE-related regulations to control the precarious handling of WEEE and prevent the importation of WEEE from developed countries in the form of second-hand devices [16].

1.2. WEEE management cycle

To better understand the WEEE problem, it is important to define the current handling practices. First, the WEEE management cycle is handled by the formal and informal sector. The formal sector is usually defined by a legal framework within a country and operates within health and safety regulations and with the proper infrastructure, on the other hand, the informal sector is unorganized and is dominated by individuals lacking the correct framework both legal and technological as well as the absence of proper documentation. This leads to improper handling of WEEE and lost opportunities in both recycling and recovery as well as exposure to hazards. The main phases of the handling cycle are collection, sorting and disassembly, and recycling and material recovery [17].

For the collection phase, in the formal sector, the collection is usually handled by associations, cooperatives, and waste companies through collection points, door-to-door collections, or retailers, this usually is part of the EPR in which the producer funds these collection and recovery programs. In the informal sector, this is carried out by individuals or scavengers who collect and transport the WEEE to the storage area for further processing. After the collection, the WEEE is sorted and disassembled. In the formal sector, this takes place in specialised facilities which use equipment and follow the safety standards. On the other hand, the informal sector tends to do manual disassembly with an aim to recover only the most valuable components. In this phase, sometimes the components are tested to be refurbished or to separate the functioning from the non-functioning parts to reuse them. The final stage of WEEE handling is the recovery of materials and recycling. In the presence of a formal framework, the disassembled components are treated for metal recovery with the recovered metals being sent to refineries and recycled. The material recovery also extends to non-metal components such as plastics and glass. Materials which are not recovered are usually sent for energy recovery through incinerators. This limits the amount of waste that is landfilled. In the informal sector, the metal recovery is done using primitive methods such as open burning of cables or acid leaching using hazardous chemicals, many of the components of WEEE are dumped or landfilled if deemed invaluable by the handlers and a small fraction may reach the formal facilities for metal refining. This also encourages the transboundary exportation of some of the WEEE generated in countries which do not have a fully developed formal sector [6], [14], [17], [18].

1.3. Impact of WEEE

The improper handling of WEEE poses a health risk to both the handlers and the society in which the WEEE ends up, this is due to the content of chemicals and materials that have direct harm or that can affect the human health due to entering the food chain. In addition, the improper handling using toxic chemicals for materials recovery without adequate personal protection equipment (PPE) and chemical waste treatment systems can aggravate the impact of WEEE on human health. Toxic metals such as lead, mercury, cadmium, and chromium affect the nervous system, kidneys, brain, respiratory system, and in some cases can cause DNA damage. Some of the plastics contained within WEEE have brominated flame retardants (BFR) which when burnt emit toxic flames. Some of the heavy and toxic metals may leak into the soil or reach nearby water streams polluting the environment and entering the food chain of the surrounding society causing further health issues [6], [17], [19]

Environmentally, proper handling of WEEE prevents hazardous materials from finding their way into the environment. In many cases, WEEE is landfilled or incinerated while in other cases it is disposed of by burning in open dumpsites [11]. Toxic chemicals from WEEE can pollute the air causing negative impacts to the air quality and the biodiversity in the region. In addition, water and soil contamination can be caused by the heavy and rare earth metals contained in WEEE [10], [16].

Socially, the hazardous materials included in WEEE threaten public health. These materials can cause kidney failure, skin problems, respiratory diseases as well as being carcinogenic, just to list a few [16]. The threats are more evident in the case where informal handling of WEEE take place. Typically, WEEE is burnt in the open air by the informal sector in addition to the acidic treatments that are used to extract the metals present [20]. In Guiyu, China, one of the world's largest WEEE handling places, 80% of children have shown symptoms of respiratory disease or lead poisoning [10].

The problem of WEEE falls directly under the 12th SDG, Responsible Consumption and Production. However, it does indirectly fulfil other goals namely the 3rd, 6th, 8th, 11th and 14th, these goals are respectively Good Health and Well-being, Clean Water and Sanitation, Decent Work and Economic Growth, Sustainable Cities and Communities, Life Below Water [6], [21]. According to the UN SDG targets, the safe handling of WEEE contributes to the reduction of deaths due to hazardous chemicals (target 3.9). The informal WEEE handling sector suffers from high levels of exposure to hazardous chemicals and the lack of personal protection equipment or safety measures when handling WEEE [14]. A common practice in the informal sector as well as the improper handling of WEEE is the disposal of the treatment chemicals or unwanted components into the environment. This can lead to leaching into the water bodies and underground water and impact the lives of those living and working in the areas nearby, thus proper handling contributes to the achievement of equitable universal access to safe drinking water (target 6.1), the reduction of pollution, dumping and the release of hazardous materials into the environment (target 6.3) and the reduction in marine pollution (target 14.1 and 14.2). Since the amounts of WEEE are constantly on the rise, their proper handling contributes to the reduction of the environmental impacts of cities through proper waste management (target 11.6). Integrating the informal sector which works in WEEE handling and adopting policies that force the safe and proper handling of WEEE contributes to their formalization, creating job opportunities, economic growth, and decent working conditions as well as the protection of workers' rights (target 8.3 & 8.8). Most important of all is the fact that proper WEEE management contributes to the minimization of the release of waste into the environment and the safe handling of chemicals (target 12.4) in addition to the reduction of waste generation through the promoting of the 4Rs (reduction, repair, recycling and reuse) through improved consumer behaviour and a collaboration between the consumer and the producer and governments to ensure the waste is safely collected, handled, recycled and reintroduced into the production supply chain (target 12.5) [22].

1.4. Shortcomings of WEEE handling

Among the challenges reported that cause improper WEEE handling is the lack of awareness about the problem as well as the absence of collection and recycling targets in most countries with only 36 countries globally which have recycling targets and 46 that have collection targets. The lack of awareness is embedded into the global trade codes, which do not distinguish between used electronics and WEEE thus opening a loophole for illegal transboundary transportation. Illegal transportation of WEEE across borders is another problem that complicates the WEEE handling process. In 2022, 65% of WEEE movement across borders was undocumented cargo from high-income countries to low-income countries which usually lack the appropriate WEEE handling infrastructure and legislation [6].

The lack of well-developed WEEE handling systems leaves the system vulnerable to the informal sector which currently dominates it leading to inefficient handling and material recovery [14], [17], [18]. It is estimated that only 42% of all countries worldwide have WEEE policies out of these countries only 82% have governing bodies that overlook the WEEE handling process and implementing the EPR. In 2022, 80% of the WEEE generated was handled informally of which 16 billion kg are estimated to be recycled informally but within a developed WEEE management infrastructure in high- and middle-income countries while 18 billion kg is handled in lower-income countries with no adequate infrastructure and the remaining 14 billion kg are disposed of or landfilled. This scanty handling by safe adequate means has resulted in the annual release of toxins into the environment such as mercury (58 thousand kg) and plastics with BFR (45 million kg) [6].

Another deficiency in the WEEE sector is the unbalanced research interest in the various aspects of WEEE. Although the amount of WEEE management-related patents has risen by fivefold between 2010 and 2022 and it is reported that publication in the WEEE sector is almost equally distributed across the four sections: collection, disassemble, recovery, and integrated process, the interest in critical raw materials recovery remains low with most of the patents being in the field of cable recycling technologies. This is partially due to the price of rare earth metals being low discouraging investments in the recycling operations on a commercial scale [6], [23].

Reporting and tracking the generated WEEE aggravate the WEEE handling issue. Considering that Europe is among the best regions in terms of reporting, their reporting rate falls short at only 42.8% of the WEEE generated which is being handled by the formal recycling sector and thus gets reported and tracked formally by authorities [6], [14]. The lack of tracking leads to unhandled WEEE ending up in other streams. For instance, in 2018 0.6 million tonnes (Mt) of mishandled WEEE reached municipal waste streams and local dumps, 1.12 Mt was recycled in unfavourable conditions, 1.1 Mt was handled as mixed metals scrap, and 2.09 Mt was illegally exported to developing countries [14].

1.5. Circular economy and urban mining

With the current implemented WEEE policies globally, which do not fully tackle the problem, the amount of CO_2 equivalent prevented is 93 billion kg [6]. This demonstrates the importance and impact proper WEEE management has and further reaffirms the need for more action within the frame of a green circular economy. Urban mining is the recovery of resources from waste instead of natural ores in the earth’s crust, it tends to close the product lifecycle and encourage a cradle-to-cradle approach. It is a process that does not only include the recovery of materials but also their refining and processing as in conventional mineral mining [6], [17]. This concept goes hand in hand with the idea of a circular economy which makes use of products at their end-of-life (EoL) by encouraging the 4Rs. Since it eliminates waste reaching landfills and rethinks how waste can be valorised and reintroduced in the production supply chain. Research in the field of urban mining has a twofold benefit. First, it promotes the recovery and reuse of materials from waste instead of having to mine them from the earth’s crust in a process that is highly disturbing to the environment. Second, the research helps identify key problems faced within the recovery process which are sometimes related to the product design, or the mixture of the materials used. Identifying such shortcomings, helps designers improve their products and promote Design for the Environment; a concept which takes into consideration the entire lifecycle of the product including its EoL and handling [17].

1.6. WEEE and Decision Support Systems

Although technological advancement has contributed to the WEEE problem by increasing the amount of WEEE generated, it is a double-edged sword that is also used to help resolve the WEEE problem. This is done through the advancement in computational power and the ability to model solutions and various criteria and is known as computational sustainability. Such an approach can simplify the numerous variables involved in WEEE handling from the technological methods to their environmental and health impacts while considering the economic aspect of each of these handling methods. This allows a more holistic approach to the WEEE problem.

One way of incorporating computational sustainability is the development of Decision Support Systems (DSSs). These are systems which assess conditions, constraints, and the relations between various factors in order to generate and recommend multiple scenarios to tackle a problem. DSSs can help support policy and decision-makers in making a more profound decision based on the suppositions of the multifactor model. Since the use of DSSs in tackling waste problems, especially the collection phase has been demonstrated to be effective [24], ergo they can be used to confront the complexity of electronic waste and offset its impacts. In order to develop such systems, it is important to have a more profound knowledge of the different aspects of WEEE. This includes the legislative framework, the handling technologies, the composition of different types of WEEE as well as the environmental and health impacts of both the WEEE and the handling technologies. Using the detailed information from the literature review, system requirements can be well-defined along with the research questions and the methodology to address the research questions. This will be discussed in detail in the subsequent sections.

Chapter 2

Literature review

2.1. European Regulations and strategies on WEEE Handling

The outcomes of the Basel convention in the 1989 highlighted the need for regulations related to the handling and cross-border transportation of hazardous materials which include WEEE [17], [25]. It also laid the foundation for the development of a framework within which WEEE can be handled. In 2008, the Partnership for Action on Computing Equipment (PACE) was founded which produced a group of guidance documents covering the areas of testing, refurbishment, reuse, and repair of computing equipment as well as the material recovery at their end-of -life in an environmentally friendly manner [26], [27]. These documents are exhaustive and describe a step-by-step process for both the reuse and the recycle of WEEE items. They emphasize the importance of clear documentation and labelling of items and components during each phase to allow to effective tracking. The document issued on material recovery went deep to highlight the materials contained within each type of computing device that the document covers and in which part of the computing device these materials are found. Such knowledge mitigates the potential hazards that manual labourers may be exposed to, and ensures adequate procedures are followed. In addition, it presents a process flowchart for an efficient material recovery including the chemicals added during the material recovery and highlighting their potential hazards [27]. These documents were meant to be used not only by legislatures and governments but also by business owners and facility managers to ensure a sound management of the handled WEEE. Following the conclusion of the PACE, the Basel Convention decided to adopt the PACE II partnership. The latter aims to build on the cooperation and achievements from the PACE and promote the further development of WEEE policies and EPR [28].

Tackling the WEEE problem and guided by the PACE, the EU developed a legal framework comprised of directives and regulations which lay down the foundation for each individual country within the EU to set their own standards. Specifically, for WEEE there exists the WEEE directive and the RoHS directive. However, these two directives exclude the handling of batteries and accumulators which are specifically discussed in the Batteries directive and the new Batteries Regulation, where the latter boosts the EU’s ambition for a circular economy and fosters its strategic autonomy. Additionally, there are the REACH regulations and the Regulation on POPs which cover some of the materials included within WEEE. Finally, the CEAP and critical raw materials act are two strategies implemented by the EU in order to secure sustainable access to materials and resources with the aim to reach climate neutrality [29], [30], [31], [32].

2.1.1. Circular Economy Action Plan (CEAP)

The CEAP is an ambitious strategy that aims to achieve climate neutrality by 2050 through the emphasise on systematic change to ensure economic resilience while promoting environmental benefits [33]. The strategy is the foundation for the European Green Deal which focuses on shifting the European economic model towards higher sustainability; this is achieved through resource efficiency, waste reduction, and supporting innovation. The action plan tackles multiple aspects. To begin with, it focuses on product sustainability spotlighting eco-design principles contributing to reduce waste at the source. It pushes for more sustainable products through a set of new legislation which promote durability, repairability and recyclability in product design. On another front, it confronts sectors with significant environmental impact and resource consumption such as electronics, batteries, packaging, textiles, and construction. For instance, the promotion of the right to repair products reduces waste generation, extends products' service life, and encourages more responsible consumption. Similar strategies were introduced to the other sectors including the revamping of the Battery directive and the introduction of the Battery regulation further discusses in detail in section 2.1.5. Clearer labelling is introduced to improve the recycling practices and further eliminate waste reaching landfills. The action plan encourages the modernization of tracking and managing of resources using digital solution such as digital product passports. For WEEE, digital products would bring further transparency across supply chains and improve tracking, planning, and recycling.

2.1.2. Waste from Electrical and Electronic Equipment Directive (WEEE)

The WEEE Directive [5] was established with the core aim to mitigate the environmental impacts of the growing stream of WEEE. Moreover, it aims to promote the safe recovery and recycling of the materials included in the WEEE while protecting the human health and optimizing the utilization of natural resources. It was established based on the 3Rs concept of Reduce, Reuse, Recycle. Thus, it promotes the sustainable production and consumption goal of the SGD. Since its establishment it has managed to reduce the usage of hazardous materials in electronics such as mercury and cadmium. The directive sets the collection rates at a minimum 45% which is then increased starting 2019 to 85% of the total generated WEEE in an EU country. It then classifies the WEEE into 10 categories as well as sets the targets for recovery, reuse, and recycling of each category. However, these categories are reduced into 6 categories at the end of the transitional period August 2018. The simplification is intended to be more general and thus includes products which previously weren't fitting any of the 10 categories. More details about the categorization and the targets can be found in Table 1 and Table 2.

Table 1: WEEE categories and their recovery targets during the transitional period until August 2018 [5]

Category during transitional period	Initial targets until August 2015
large house appliances	85% recovery- 80% recycled
small household appliances	75% recovery -55% recycling
IT and telecommunications equipment	80% recovery- 70% recycled
consumer equipment and photovoltaic panels	80% recovery- 70% recycled
lighting equipment	75% recovery -55% recycling
electrical and electronic tools	75% recovery -55% recycling
toys and sport equipment	75% recovery -55% recycling
medical devices	75% recovery -55% recycling
monitoring and control instruments	75% recovery- 55% recycling
Automatic dispensers	85% recovery- 80% recycled

Table 2: WEEE categories and their recovery targets after August 2018 [5]

Categories from August 2018 onwards	Targets from August 2018 onwards
Temperature exchange equipment	85% recovery- 80% prepared for re-use and recycled
Screens, monitors, and equipment with screens greater than 100 cm^2	80% recovery- 70% prepared for re-use and recycled
Lamps	80% recycled
Large Equipment	85% recovery- 80% prepared for re-use and recycled
Small equipment	75% recovery- 55% prepared for re-use and recycled
Small IT and telecommunications equipment	75% recovery- 55% prepared for re-use and recycled

According to the directive, it is the producers' responsibility to handle and finance the generated WEEE from their products they put on the market, this concept is known as Extended Producer Responsibility (EPR). The directive also requires continuous reporting and monitoring of the electronics put on the market as well as those collected as WEEE and handled at their end-of-life. Such reporting contributes to the assessment and verification that the EU countries are meeting the collection and recovery targets set forth by the directive. Among the other targets of the directive is to promote the high level of recycling and recovery, thus recycling of materials should allow it to be used in new products and not downgrade it.

Regarding the treatment of the collected waste, the directive requires a minimum of selective treatment and the removal of fluids from the collected waste. These materials include but not limited to mercury, batteries, plastic containing brominated retardants, external electric cables and components containing radioactive substances. In case the treatment will take place abroad, the directive lays out rules that ensures the safe handling and treatment in the destination country.

2.1.3. Restriction of Hazardous Substances Directive (RoHS)

Since part of the tackling of the WEEE problem is the reduction of the waste generated, the RoHS directive sets restrictions on using certain materials in electronical and electronic equipment and their tolerated limits. These materials are generally hazardous and currently the list includes 10 materials shown in Table 3 along with their tolerated limits. Such restriction is applied on all electrical and electronic components that are put on the market except for special cases explicitly highlighted in the directive. Generally, the exceptions are given to products which cannot have those materials substituted with content limits being applied and closely monitored. Falling within those exemptions are solar PVs used commercially or for industrial or residential purposes. The directive is complementary to the WEEE directive which promotes the reduction in waste and the materials used in general as well as the proper collection and handling of the waste. The scope of the directive also covers the obligations and responsibilities borne by the manufacturers, importers and distributors which include the reporting and demonstration of compliant products using a "CE" label and proper identification [34].

Table 3: Restricted materials under the RoHs directive and their tolerated values by weight [34]

Material	Tolerated value by weight in homogeneous materials
Lead	0,1%
Mercury	0,1%
Cadmium	0,01%
Hexavalent chromium	0,1%
Polybrominated biphenyls (PBB)	0,1%
Polybrominated diphenyl ethers (PBDE)	0,1%
Bis(2-ethylhexyl) phthalate (DEHP)	0,1%
Butyl benzyl phthalate (BBP)	0,1%
Dibutyl phthalate (DBP)	0,1%
Di isobutyl phthalate (DIBP)	0,1%

2.1.4. Registration, Evaluation, Authorization, and Restriction of Chemicals regulations (REACH)

The REACH regulation is concerned with the proper identification of chemicals put on the market and their properties. The regulation was established to ensure the safety and health of humans and the environment and to encourage the innovation for new chemicals. As the name implies such identification is made through a series of processes without which materials are not allowed to be used. Namely the registration of the material, the evaluation of its properties and finally the authorization to allow this material on the market or to restrict its usage to certain products or below certain amounts to limit its presence on the market. The information needed can be provided by the producers or importers and include the documentation, risks, and disposal for such materials.

For the chemical safety assessment of a substance assessment for the human health hazard, physicochemical hazard, environmental hazard as well as persistent, bio-accumulative and toxicity. More details for the tests needed for these categories can be found in Table 4. If the materials are being moved downstream through the supply chain, the supplier is required to provide the downstream users with a compliant safety data sheet.

The restrictions and responsibilities put on importers and manufacturers are exempt in case of research and development as long as the material is still in natal phase. The exemption is also valid for manufacturers and importers as long as the total tonnage of the material put on the market is below 1 ton/year per producer or manufacturer and the concentration of these materials is within limits. Other exemptions also apply to polymers which are not required to be registered [35].

Electronical and electronic equipment are not directly covered by the REACH regulation; however, many chemical substances they enclose are covered by the regulation.

Table 4: Minimum material assessments required by REACH based on category for the registration of a material [35]

Hazard type	Criteria to be tested and verified
Human health hazard	1. Absorption, metabolism, distribution and elimination 2. Acute toxicity 3. Irritation (skin, eye, respiratory tract) 4. Corrosivity 5. Sensitization (skin, respiratory system) 6. Repeated dose toxicity 7. Carcinogenicity, mutagenicity, toxicity for reproduction
Physicochemical hazard	1. Explosivity 2. Flammability 3. Oxidizing potential
Environmental hazard	1. Aquatic (including sediment) 2. Terrestrial 3. Atmospheric 4. Food-chain accumulation (secondary poisoning)

	5. Microbiological activity of sewage treatment systems 6. Degradation 7. Bio accumulation

2.1.5. Batteries Directive and the New Batteries regulation

The Batteries directive is concerned with the end-of-life handling of batteries and accumulators; hence it goes hand in hand with the WEEE directive. Similar to the RoHS, the batteries directive restricts the use of batteries that contain mercury and cadmium. A restriction that is exempted if no alternative can be used [36].

The New Batteries regulation is a transformative milestone binding industrial practices and sustainability goals paving the road for benchmark circular economy polices. The regulation came into effect in 2023, and it comes as part of the European green deal vision which aims to promote circular economy and achieve climate neutrality through the introduction of a comprehensive approach to battery management addressing environmental, economic, and social dimensions [7]. The new regulation is a step forward towards better implementation since, unlike a directive, it is binding to all member states of the EU which ensures conformity and consistency. The regulation covers the entire life cycle of batteries from design to production and recycling unlike the old directive which focused on the end-of-life phase. In addition, the scope of the regulation now includes new categories which were not addressed previously such as batteries of light transport like bikes and scooters. From a sustainability point of view, the regulation mandates the use of fewer harmful substances and to limit sourcing materials from outside the EU fostering the EU's raw materials independency. Recovery of specific materials is also explicitly addressed by the new regulation; ambitious targets have been set for the recovery of lithium, cobalt, copper, lead and nickel. As a first step, by 2027, the target for lithium is set to 50% and increases to reach 80% by 2031, as for cobalt, copper, lead and nickel the 2027 target is 90% and increases to 95% by 2031. The collection targets are also set for the new category of batteries of light transport to reach 73% by 2030. Further measures were taken to reduce waste and extend the service life of products by introducing a mandate to make portable batteries in devices easily removable and replaceable. Battery passports are introduced using QR-codes in addition to increasing transparency and consumer awareness using performance labels. Finally, a key point introduced in the new regulation is the requirement by companies to conduct due diligence to address environmental and social risks with a focus of the recovery of raw materials and supply chain practices. This requirement helps address a growing concern about the ethics in some supply chains sources from beyond the EU territory. This reiterates the accountability of produces and the nurtures the concept EPR previously introduced by both the WEEE directive and the batteries directive. The legislation on batteries complements the WEEE directive by requiring a minimal treatment of batteries enclosed in electronics treated under the WEEE directive through their removal from the WEEE product.

2.1.6. Critical Raw Materials Act

The Critical Raw Materials Act was introduced in 2024 by the EU to combat the EU market's reliance on materials deemed critical to industries such as green and digital technologies, thus securing access and ensuring resilience [37]. The critical raw materials (CRM) are based on a list that is updated at least every 3 years by the EU commission. In the fifth and most recent version in 2023, 34 materials are present on the list including copper and nickel which are considered strategic raw materials as they do not meet the thresholds for CRM. The list also includes titanium metal and silicon metal both heavily present in WEEE. The act aims to boost domestic capacity by 2030 through setting benchmarks for strategic raw materials supply chains. 10% of the EU demand for extraction and 40% for processing are to be met by the domestic market as well as 25% of the consumption should be sourced from recycled sources. It combats the reliance on a sole provider by putting a ceiling of 65% of a material to be sourced from a single third country. The act requires stress-testing and constant monitoring to ensure preparedness to supply risks. Sustainability remains at the core of the CRM Act through the promotion of collection, recycling, and circularity of wastes rich in CRM, hence creating a secondary source for those materials. This empathizes the importance of urban mining of WEEE and puts it at the core of the CRM Act. Since WEEE contains lithium, nickel, cobalt, and rare earth metals. The act requires the assessment and reporting of the amount of CRM recovered from WEEE. The role of EPR in the recovery of such CRM is reiterated and emphasized with strategic projects that include urban mining falling under the set criteria for funding and national programs. The act highlights the current practice of WEEE exportation to third countries and disincentivises it given the imminent loss of resources and CRM associated with such practice. Recovery projects are to be implemented with sustainability in mind, ensuring respect to the environment and its protection as well as minimising the social impact of the project and respecting human rights.

2.1.7. Regulation on persistent organic pollutants (POPs)

The regulation on persistent organic pollutants indirectly applies to WEEE within the EU [38], since WEEE contains POPs that are usually present as flame retardants [39], [40]. The regulation aims to strict the production, use and disposal of POPs applying also to unintentional byproducts hence ensuring the protection of both the human health and the environment. In addition to the prohibition and restriction of the use of POPs, the regulation requires the safe handling of wastes that contain POPs minimizing their release into the environment and ensuring their proper disposal or recycling following strict environmental standards. The regulation extends to stockpile management of products which contains POPs to avoid their release into the environment. This is further controlled through regular monitoring and reporting which is required by EU countries for compliance and limiting of their levels in the environment. For WEEE, the guidelines of the regulation would require the safe handling of the components of WEEE which contain POPs, ensure their safe storage and sound disposal or recycling as well as restrict their exporting based on the guidelines set by the EU to guarantee the safe handling in the receiving country.

2.2. General WEEE management technologies

Given the richness of WEEE in materials and the legislations in place to handle them, technology has evolved in order to fulfil the needs of the WEEE handling sector offering handling techniques which are continuously improving in efficiency[6].

Handling methods can be divided according to two different categories; first, based on the order thus, divided into pre-treatment methods and post-treatment methods. Otherwise, they can be divided based on the technology they use; hence, hydrometallurgical, pyrometallurgical, bio-metallurgical, electrometallurgy, and mechanical [17].

Generally, WEEE handling starts by the collection followed by a category-based separation into the different WEEE categories then a dismantling phase follows which can be manual or automatic. Afterwards comes the pre-treatment phase to separate the different components and finally the post-treatment phase which includes the material recovery and refining [41]. A brief summary of the handling process and the techniques used is shown in Figure 1.

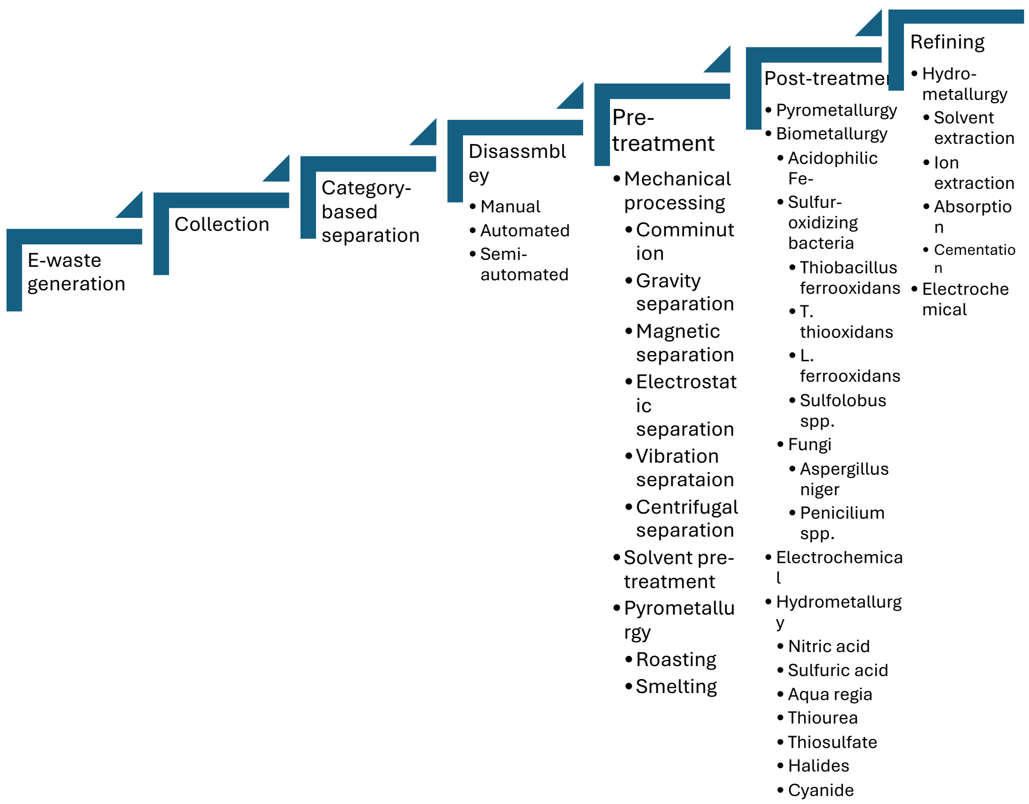


Figure 1. Summary of the WEEE handling process and the most common techniques used for each phase

2.2.1. Pre-treatment

Pre-treatment methods are those used to separate the different components and materials in order to prepare for the material recovery phase. A pre-treatment phase can be composed of a single step or multiple steps with different technologies all aimed at obtaining a better separation grade [17]. Pre-treatment techniques can be mechanical, chemical or pyrometallurgical. These techniques can be combined together to mitigate their drawbacks and improve efficiency [42].

Mechanical methods are aimed at reducing the size of the waste to offer better subsequent material separation. Commonly used mechanical processes are the crushing, grinding or shredding of the WEEE, which can be achieved using swing hammers [43]. The size reduction phase of WEEE is essential in the treatment process as it liberates the components and materials preparing them for the material separation phase [44]. For the separation of components, hot air heating, solder bath heating, hot fluid heating and solder dissolution techniques are used [45].

The material separation phase using mechanical techniques helps increase the concentration of materials which in turn increases the efficiency of the subsequent material recovery and refining processes. It also allows the recovery of some materials such as glass and plastics to be directly recycled after the mechanical treatment process [46]. Gravity separation is among the used methods for material separation making use of the difference in physical properties between the different materials found within the WEEE [43]. The process can be carried out using water flow tables or air classification; however, the process is highly dependent on the quality of the precedent size reduction process as the particle size directly influences the gravity separation process [47]. One shortcoming of the water flow table used in gravity separation is the high consumption of water.

Froth flotation is another technique used in separating the different materials making use of their hydrophobicity. Differently from water and gravity separation techniques, froth floatation does not depend only on the relative density of different materials [48]. The process is used for the separation and recovery of both copper and plastics [43], [48]. To create the froth needed for the separation process, wetting agents are used some of which are hazardous to both humans and the environment such as cyanide and potassium amyl xanthate [49].

As the name implies, magnetic separation uses the magnetic property of materials to separate ferrous metals from non-ferrous metals and nonmetals using giant magnets [17]. Magnetic separation is usually combined with other separation techniques [50]; since on its own it cannot separate metals beyond ferrous and nonferrous in addition to being affected by the agglomeration of particles [43].

Electrostatic separation can be carried out using various techniques including, eddy currents, triboelectric or corona electrode technique; these techniques make use of the electrical conductivity of particles of different materials to polarize and sort them [51]. Electrostatic separation is environmentally friendly producing streams with high purity as well as separating mixtures of nonferrous materials which magnetic separation fails to separate [43]. Other dry mechanical separation techniques are vibration separation and centrifugal separation; in the former, vertical vibration is applied to crushed WEEE particles separating them into metal and non-metals while in the latter a centrifugal force is applied to separate different materials [52].

Beyond mechanical processing techniques, solvent pre-treatment techniques are also used to liberate the metals from the organic components found in WEEE. The process uses solvents, mainly organic, to achieve the swelling effect or dissolve the epoxy resin [53]. Detailed description of the solvent pre-treatment techniques and the used solvents is discussed with a focus on Printed Circuit Boards (PCBs) in section 2.4.2.

Finally, pyrometallurgy can be used as a pre-treatment phase for material separation to get rid of the organic components in WEEE and retrieve the metals by heating the WEEE at very high temperatures [54]. However, it is usually applied as a standalone treatment process without combining it with other pre-treatment techniques or only a material refining phase follows [43]. Pyrometallurgy includes roasting, smelting or pyrolysis which are all techniques with high energy demand making it expensive besides the environmental concern associated to the produced byproducts and polluting gases [50].

2.2.2. Post-treatment and refining

Besides the use of pyrometallurgy as a post-treatment method, hydrometallurgy has been widely adopted. Hydrometallurgy is the process of using acids and caustic leaches to extract metals with high purity in a chemical treatment process [46]. Among the popularly used chemicals are nitric acid, sulfuric acid, aqua regia, thiourea, thiosulfate, halides, cyanide [17].

Although hydrometallurgy can be time consuming and require the use of large amounts of chemicals, they offer favourable results and high controllability regarding the materials to extract [50].

Chemical processes can also be used in the refining phase after the metal extraction incorporating processes such as solvent extraction, ion exchange, adsorption, and precipitation [17]. Precipitation is the most common technology used in removing dissolved (ionic) metals from solutions. It retrieves the desired metal through the addition of precipitating agents to a leaching solution converting it to an insoluble form by the chemical reaction between the soluble metal compounds and the precipitating reagent. Solvent extraction, on the other hand, is a purification method that is used to separate compounds, based on their relative solubilities in two different immiscible liquids which usually carry the desired metal [17].

Bioleaching also known as bio-metallurgy is a process that uses microorganisms to dissolve metals from ores and other sources into ions facilitating their further recovery [17]. The process uses different types of microorganisms such as acidophilic Fe-, sulphur -oxidizing bacteria (Thiobacillus ferrooxidans, T. thiooxidans, L. ferrooxidans…etc.), or fungi (Aspergillus niger, Penicilium spp.) [55]. Bioleaching is seen as environmentally friendly and has low energy and operating costs making it an attractive treatment method even with the long treatment periods needed [17].

Electrowinning, electrodeposition and electrorefining are commonly used electrochemical processes which are favoured in the WEEE handling sector since they offer high selectivity in addition to the reduced consumption of chemicals and energy [56]. In addition to these processes, electrodialysis and electrocoagulation are sometimes used for recovery of rare earth metals [17].The process makes use of the difference in properties between the different metals to oxide and reduce them by passing an electric current in an electrolyte which separates the metals into anodes and cathodes [57]. Electrochemical processes can be performed using aqueous solutions as in the case of extraction of copper, zinc and cobalt which makes it inexpensive and more environmentally friendly [56]. In addition, ionic liquids can be used to lower the operating temperature; this is usually used to extract metals like indium, gallium and palladium [56]. Electrowinning differs from electrorefining in that the former extracts pure metals dissolved in the leach electrolyte while the latter dissolves the metal from an anode contaminated with impurities and collects it on a cathode with high purity by plating it [57].

2.3. Solar Photovoltaics

Solar photovoltaic (PV) systems are becoming essentially a clean and alternative source of energy [58]. Simply put, the idea of generating electricity using solar energy is based on using the photons received from the sun to excite the electrons in a semiconductor causing their circulation which generates an electric current [59]. The efficiency of power conversion is dependent, among other external factors, on the type of material and technology used in the fabrication of solar PVs which are categorised in four generations [60].

The first generation of solar PVs is the most basic and it uses monocrystalline and polycrystalline silicon [58]; they comprise 86% of current solar PV market and have an efficiency range of 15-20% [59]. Second generation Solar PVs are known as "thin film" and they use amorphous silicon (a-Si), copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and cadmium sulphide (CdS); they have an efficiency of about 20%, are less expensive and thinner which makes them cost effective [59]. Under third generation PVs fall more advanced materials such as GaAs, GaInP, and dye-synthesized solar cells (DSSC) while the fourth generation is known as "inorganics-in-organics" which includes perovskite, where both generations are still under extensive research with efficiency of about 12% for third generation and 16% for fourth generation PVs [59].

A solar panel is typically made up of a back sheet and a top layer of glass substrate between which the semiconductor material is sandwiched along with the conductive layer which connects the P-V junctions, the aluminium frame, and the encapsulant material [61]. Among the materials embedded in solar cells are glass, lead, iodine, tin, and gold; this composition changes based on the technology of the solar cell [62].

In crystalline silicon panels the glass represents 76% of the total panel weight, while the aluminium frame is about 8%, the encapsulant and back sheet represent 10% of the panel weight, and the silicon cells and the conductors made of copper represent 5% and 1% respectively [61]. Finally, a very low amount of silver, tin and lead which represent less than 0.1% combined. The composition changes in the case of CIGS panels where glass content is higher representing 89%, lower aluminium presence at 7%, and encapsulant represents 4% [61].

At the end of their lifetime, solar PV systems are treated as WEEE. Although only 1% of the total installed systems have reached their end of life, with the life expectancy of solar PVs a significant amount of solar PV systems is estimated to enter the waste stream around the 2030s [62]. Many of the components included in solar PV systems, such as the aluminium frame and the wirings, can be handled and recycled without the need for specific processes tailored for solar PVs, yet the solar cells remain subject for research in material recovery due to the scarcity and raw materials and the requirements by legislations for an environmentally friendly handling of WEEE [62]. High collection rates are highlighted as the main factor which affects the feasibility of whatever EoL handling process that follows with scenarios which avoid or limit landfilling being more favourable; however, the lack of clear vision for the applications of the recovered materials leads to their dissipation and economic losses [9].

Currently, treatment processes are developed mainly for crystalline silicon and CdTe [63]. For silicon crystalline a sequence of thermal and chemical treatment is often used [64]. However, organic solvent treatment is becoming an alternative with the scope of recovery of the silicon modules after liberating them from the EVA layer [63].

A common multiphase recycling process for CdTe solar panels starts with the size reduction of the panels then the removal of the glass and the laminate using mechanical methods after which chemical treatment of the semiconductor using peroxide and acid is applied [62]. A reported treatment process for CdTe uses multiphase size reduction starting by shredding then hammer crushing which is then followed by chemical treatment using sulfuric acid and hydrogen peroxide, the glass part is then recovered by sieving and the metals are recovered by leaching [63]. Another approach with a slightly different sequence starts by delamination followed by de-coating and finally the extraction of metals [63]. Multiphase size reduction processes have been reported as advantageous helping in 80%-85% improved glass recovery in case of double crushing, and for triple crushing the amount of waste which required thermal treatment was reduced to 62% instead of 85% in the case of single crushing [63].

For CIGS, innovative techniques can be used to recover selenium, indium and gallium; the process starts by crushing then chemical treatment using acids followed by precipitation and filtration in order to extract the materials with the use of surfactants and electrodeposition [65]. This process was reported as advantageous as it recovered valuable materials and avoided the conventional process of landfilling the residual waste after thermal treatment. A similar innovative process for CdTe offers environmental advantages to the conventional process due to the elimination or limiting of landfilling [65].

2.4. Printed Circuit Boards

2.4.1. Composition

Among the components dominating the generated WEEE is PCBs. However, they might not be as appealing to recyclers as other components as the composition of ferrous components is low compared to the majority plastics, glass, and resin [16]. A PCB consists of a substrate made of multiple layers typically made of FR4 a fiberglass-reinforced epoxy resin, phenolic resin or polyimide ensuring the substrate is insulated and have the needed mechanical strength to support the mounted components [66]. Between each layer of the substrate lies the solder masks and silkscreens as well as copper which due to its high conductivity is used for the connecting pathways, also known as traces, between the components [67]. The complexity of the PCB increases with the complexity of the application [68]; hence, the presence of single or multiple layers of copper with the latter being more commonly found [69].

The solder masks act as insulation between close connecting paths of copper in addition to protect the PCB from oxidation while the silkscreen has the more informative role being used to print necessary information on the PCB such as the component labels crucial for assembly and troubleshoot [70].

From an economic perspective, the materials included in WEEE was estimated to the value of 91 billion USD of which almost 40% is concentrated in the PCB [6], [11]. The economic value also extends to the fact that metals found in WEEE has higher concentration compared to that extracted from their natural ores [10], [11]. The recovery of these materials provides an alternative source to the primary resources which allow a continuous supply of precious and rare materials [14]. Annual demand for Rare-earth ores, used in extracting rare earth metals which are extensively used in EEE, reached 118 thousand tons in 2014 and is expected to continue increasing to 200 thousand tons in 2025. In 2018, 90% of the demand on rare-earth ores was fulfilled by China and the estimated value of the produced ores in 2021 was 5595.32 million USD with Neodymium being the most widely used rare-earth metal in EEE [16].

The need for processes of high recovery rate of materials from WEEE in general and PCBs in particular is justified both economically and by legislation. In the geographic context of the EU, the WEEE directive requires material recovery from WEEE to reach 85% while the Circular Economy Action Plan incentivizes recycling and remanufacturing [5], [33] . In addition, many of the materials found in PCBs are on the critical raw materials list notably copper and nickel [30].

Just as in the case of other types of WEEE, PCBs can be treated using pyrometallurgical, hydrometallurgical or a mix of both methods. Hydrometallurgical methods recover metals by dissolving them from solid substrate allowing a high level of selectivity depending on the type of leaching agent used which can be acids, alkalis, or complexing agents such as ammonia, sulfuric acid and nitric acid widely used for copper recovery [71], [72], [73]. This selectivity is advantageous in the case of PCBs given the presence of many different metals permitting the easy recovery and separation of these metals. This process usually follows an initial mechanical crushing process to reduce particle size and to liberate the metal from the substrate exposing it to the leaching agent [66]. The efficiency of the treatment process is dictated by multiple factors such as temperature, pH value, weight to volume ratio of the solution, leaching agent concentration, and the stirring speed [54], [74], [75].

2.4.2. Chemical pre-treatment handling techniques

Enhancing hydrometallurgical treatment efficiency has been the topic of various research, and one approach to achieving it is through an innovative two-step treatment methodology.

This method combines initial mechanical size reduction of waste PCBs with a subsequent chemical pre-treatment phase utilizing specific solvents. The primary mechanism involves the application of organic solvents that interact with the PCB's resin matrix, causing it to either expand or break down. This interaction is particularly significant as it exposes previously hidden metal layers within the PCB structure, effectively increasing the metal surface area available for treatment. This increased exposure significantly enhances the effectiveness of subsequent leaching processes [76]. Beyond metal recovery, solvent pre-treatment has demonstrated additional benefits in the field of WEEE management. Recent research has shown that this technique is particularly effective for removing bromine compounds from various electronic waste plastics, including those found in PCBs and other electronic equipment [39], [77], [78], [79], [80]. This debromination capability represents a significant advancement in the sustainable processing of electronic waste materials.

Research has explored various organic solvents in the pre-treatment of PCBs. Several investigations have demonstrated the effectiveness of different solvents, including dimethyl sulfoxide (DMSO) [80], N-methyl-2-pyrrolidone (NMP) [81], dimethylformamide (DMF) [82], and dimethylacetamide (DMA) [83]. Other techniques also include the use of supercritical fluids. The efficiency of adding an organic solvent pre-treatment phase have been reported in various patents.

For instance, one patent proposed a multistage treatment process where each phase consists of an oxidizing agent, leaching and a passivating agent [84]. The first treatment phases by using alkane sulfonic acid as an oxidizing agent, followed by leaching using nitric acid and finally the use of triazole derivative as a passivating agent. This is then followed by a second treatment phase where oxone or persulfate salt is used as oxidizing agent, then a leaching agent is chosen based on the metal in question from ammonium chloride, sodium chloride, lithium chloride, potassium chloride, ammonium sulfate, hydrochloric acid, sulfuric acid, or a combination of two or more of these agents. The phase ends with the use of an organic solvent or a mixture from one of the groups of alcohols, ethers, pyrrolidinones, glycols, carboxylic acids, glycol ethers, amines, ketones, aldehydes, alkanes, alkenes, alkynes, amides.

Another patent defines the use of one or more of dimethylformamide, dimethylacetamide, cyclohexanone, y-butyrolactone, dimethyl sulfoxide, N-methyl-2-pyrrolidone. However, the process included pre-swelling for 17 hours followed by swelling for 20 minutes in a low-pressure reactor at a temperature between 60°C to 250°C and stirring of 600 to 1000 rpm and a waste to solvent concentration of 1:2 g/ml [85]. This process is lengthy, uses high temperature and has a reported metal yield of between 80% and up to 95%.

Other patents use dimethyl sulfoxide combined with other chemicals such as acetone, ethylene bis stearamide (EBS) and methylene (3,5-di-tert-butyl-4-hydroxyhydrocinnamate) to retrieve the non-metals present in PCBs; where the recovered non-metals can be used as stuffing for thermoplastic polyethylene resin, mixed with cement and sand to produce road barriers, or a dry powder heating insulating material [86]. The use of dimethyl sulfoxide was also patented as a consecutive step after pyrolysis to remove the epoxy resin and ease the recovery of copper foil, metals, and fibre glass from the crushed PCBs [86].

Beyond dimethyl sulfoxide, the use of one or more of organic solvents was reported as a method for harmless treatment of PCBs [87]. The process starts by reducing of the PCBs to a size of about 5-10 mm, afterwards thorough washing with water takes places before the first treatment using inorganic solvents such as one or a mix of nitric acid, sulfuric acid, and hydrochloric acid at a molar concentration of 2-4 mol/L, 45°C -55°C temperature and time ranging between 2 and 4 hours. This leaching process is then followed by another one using another mixture of the aforementioned inorganic solvents at elevated temperature between 75°C and 85°C and for a period between 1 and 4 hours. The process is concluded by adding organic solvent solution of one or more of ethyl formate, propyl formate, ethyl acetate, propyl acetate, ethyl propionate and ethyl benzoate to extract the epoxy resins and glass fibre.

Organic solvent pre-treatment has been reported to be used with smaller sized pieces of PCB of about 3-7mm. One or more of the organic solvents N,N-dimethylformamide, methyl ethyl ketone, tetrahydrofuran, or stripOxy is added to the PCB pieces where for each litre if the solvent solution about 70gm to 120gm of PCB pieces is added with 900 rpm stirring and treatment time between 30 and 120 minutes at 130°C. This process reports metal recovery of 99.99% using electrostatic separation [88].

A simpler single phase pre-treatment process was reported to use 8:1 NMP to resorcinol and at least 3:1 ethylene glycol to salicylic acid. However, the temperature range is 110°C and reaches up to 210°C which is relatively high [89].

The use of ethylene glycol was reported in another patent which specified the different conditions for effective swelling. The reported conditions were 3 hours for a pre-treatment at 25°C, which gets reduced to 1 hour in case of elevated temperature of 100°C. The patent also uses propyl carbinol for swelling at under 50°C for 2 hours or a mixed solution with water at 10:1 bringing to the swelling time to 4 hours. N-butyl acetate was also used at temperature below 100°C for 3 hours to dissolve the epoxy mold [90].

Other solvent mixtures reported were the use of pyridine in the case of presence epoxy resin, methyl acetate against polyvinyl chloride, and methylcyclohexane where polyethylene is present [91].

In addition to them being reported in various patents, these organic solvents have been a subject of extensive investigation separately as discussed in the following subsections.

2.4.2.1. Dimethyl sulfoxide

Organic solvents such as DMSO were applied as a pre-treatment on the fragments of bare PCBs obtained from motherboards of sizes between 16 mm^2 and 400 mm^2. The optimal conditions achieved were at a temperature of 145°C for 60 minutes with a solid-to-liquid ratio of 1:7 on the smallest fragments of 16 mm^2. The process allowed the regeneration of DMSO after the treatment process as well as the dissolving of the brominated epoxy without dissolving the metals [80]. A similar process was applied on particle sizes between 15- 20 $mm^2$of bare motherboards with a solid-to-liquid ratio of 1:2 and achieved better results of complete delamination after only 30 minutes at 170°C [92].

Another attempt to use the DMSO was applied on fragments of bigger size of PC motherboards, 1-1.5 cm^2 and 2-3 cm^2pieces. The study concluded that a complete delamination could be achieved for the smaller-size particles at 60°C after 210 minutes, at 90°C after 60 minutes or at 135°C after 10 minutes. As for larger particles of size 2-3 cm^2, delamination was achieved at 60°C after 480 minutes, at 90°C after 90 minutes and at 135°C after 20 minutes. The study also concluded that the use of DMSO does not result in a reaction with metals but only dissolves the brominated epoxy resin [93]. This was confirmed in another study that assessed the use of DMSO on stripped PC motherboard particles and concluded the optimal conditions to be at 90°C for 90 minutes with a solid-to-liquid ratio of 1:2 and a particle size of 6 mm [81]. In all attempts, the experiments were carried out on relatively large particle sizes and not powder PCBs. It is important to mention that DMSO has a high ability to penetrate human skin, and its vapours are heavier than air so it should be handled with caution [82].

2.4.2.2. Dimethylacetamide

The use of DMA on PC motherboards of large dimensions of around 1 cm^2 was evaluated [94]. In the preparation for the study, it was found that extremely fine crushing of PCB (150μm), although liberating the metals completely, results in a significant loss of metals in the fine fractions, thus this experiment avoided the crushing process. One of the difficulties reported when treating such large pieces of PCBs is the presence of through holes and pins on the PCB which hinder the swelling process. The conditions established were a solid-to-liquid ratio of 1:10 and time up to 75 minutes at a temperature of 160°C.

Evaluation of the pre-treatment of even bigger PC motherboard sizes was made on pieces of 100-1600 mm^2. The Solid to liquid ratio is 3:10 at 160°C. For smaller pieces of 100 mm^2 optimal time was 150 minutes and for the larger ones of 1600 mm^2, the time was 420 minutes [83].

2.4.2.3. Dimethyl formamide

DMF was tested as a solvent for brominated epoxy resins due to its advantages in comparison to other solvents. Among the advantages of DMF is that it can be easily regenerated. The optimized conditions obtained from the experiments are at a temperature of 135°C, particle size of 1 cm^2 and time of 240 minutes with a solid-to-liquid ratio of 300g/L [82].

2.4.2.4. N-methyl-2-pyrrolidone

The use of NMP was tested in a comparative study to evaluate the results against that of DMSO. The study showed that NMP is a better pre-treatment solvent than DMSO and established the optimum conditions to be a solid-to-liquid ratio of 1:5 at a temperature of 100°C for 90 minutes for particle size of 4 mm/16 mm^2 which can be achieved through a sieve of 8 mm [81], the particles used were obtained from stripped PC motherboards. Health risks associated with NMP that constitute a drawback to the process are reproductive disorders as well as being carcinogenic [82].

2.4.2.5. Supercritical fluids

The use of supercritical fluids for the removal of the organics as pre-treatment was demonstrated to be an effective eco-friendly method. On crushed RAM PCBs of size around 10-20 mm, ethanol was used at 300°C for 60 minutes with a solid-to-liquid ratio of 1:20; within the same study acetic acid was then used for leaching of the various metals contained with optimum conditions defined as 1.2M of acetic acid and 10% hydrogen peroxide with solid to liquid ratio of 1:20 at 50°C for 5 hours and a stirring of 350 rpm [95]. It is important to mention that treatment of brominated epoxy resins above 250°C compromises its stability and can cause pollutant emissions [82].

2.5. Computational sustainability and Decision Support Systems

The use of ontology-based Decision Support Systems (DSSs) is becoming an increasingly used approach. Since ontologies facilitate uniformity and interoperability across various sectors given their structured, and semantically rich representation of domain-specific knowledge. An ontology functions as a universal framework since it is made up of a cohesive language, therefore enabling a seamless integration of knowledge bases and fostering effective communication across disciplines within the same sector and beyond [96], [97], [98], [99].

Classes, relationships, and instances are the building blocks of ontologies. Classes represent abstract concepts, with instances serving as specific occurrences of these concepts. This allows the clear definition of broad categories and the drawing of connections amongst them, thereby supporting a scalable, adaptive knowledge framework [96], [100].

There are multiple languages that can be used for the development of ontologies such as DAML+OIL, DAML-ONT, and OWL. However, OWL is particularly common due to its compatibility with W3C standards, including interoperability and user accessibility. In addition, the possibility to automatically derive direct and indirect relationships using the reasoning capabilities allow for continuous expansion and persistent precision [96], [97].

Ontologies have increasingly demonstrated their utility across diverse fields within the realm of sustainability. In the construction sector, for example, ontologies based on Life Cycle Analysis (LCA) facilitate assessments of composite materials, such as cement-steel-slag mixtures [101], or to support energy and carbon optimization in buildings [102]. Modular ontologies also support the creation of digital product passports in the building sector, contributing to resource conservation and emissions reduction efforts [98]. Across the life cycle of products, ontologies provide the semantic structure necessary to execute detailed LCA, enhancing sustainability through optimized resource usage [103]. Cross-domain applications extend further, with data integration from fields like meteorology, urban planning, and process engineering offering improved decision support in areas such as industrial emissions and air pollution management [100], or via sharing resources and decreasing industrial waste by realising eco-industrial parks [104]. Within the domain of urban sustainability, the USDA ontology provides a framework that integrates specialized ontologies, stipulating a holistic understanding of interconnected urban systems and facilitating comprehensive decision-making through the amalgamation of these specific ontologies into a single high-level ontology

[105]. In the nexus between Water, Energy and Food, an ontology was used to project a system's sustainability and to aid decision-makers in optimizing the system inputs to minimize the trade-offs and guarantee sustainable growth [106].

The waste management sector also benefits significantly from ontology-driven DSSs, particularly in areas such as municipal solid waste management [107], [108], selective recycling processes [109], and optimization of treatment facilities [110]. Specific DSS implementations within WEEE management illustrate the system's capacity to support complex processes, such as LCD monitor disassembly and other electronic waste protocols [111].

Despite these advancements, many existing DSS solutions are tailored to highly specific cases, thereby limiting their interoperability and scalability. Given the complexity of WEEE, including its diverse material composition, potential hazards, and myriad treatment methodologies, no DSS has managed to address WEEE. Establishing an ontology-based foundation within DSSs is thus indispensable for fostering integrated and informed decision-making in WEEE management, supporting a framework that is both scalable and capable of incorporating future advancements in WEEE handling and sustainability research.

Chapter 3

Methodology

3.1. Research gap

After the thorough study of the literature available regarding the WEEE management and the challenges faced by the sector, a few gaps were identified as of interest to this research.

There is a clear fragmentation of the WEEE ecosystem which results from WEEE spanning over multiple domains. This has led to WEEE management systems treating the different domains of WEEE, such as technological, material and hazard domains, as isolated entities regardless of their interconnected nature contributing to inefficiencies and derailing the sector from being sustainable. This shortcoming is due to the lack of a practical integrated multi-domain system which consolidates the knowledge from these domains. Even with the presence of domain experts, it is quite hard to find someone who possesses a deep and expert level knowledge across all domains.

The literature review also revealed that on the computational and IT level, there has not been attempts to use computational sustainability in order to develop a multi-domain DSS (whether ontology-based or using other technologies) which can bridge the currently disconnected domains of the WEEE ecosystem; specifically, the technological, materials and hazard domains [107], [108], [109].

On attempting to look up different ontologies that cover the three domains of interest and to combine them together to use them as a core for a comprehensive WEEE DSS, the problem of scalability and reusability of the existing solutions surfaced as a third gap [112].

Another challenge identified from the literature review is the overgeneralization of the material content in the data available regarding WEEE. Existing material composition data tend to be generic, ignoring potential critical variations across the categories and subcategories of WEEE, and in some cases variations among different models of the same categories [41], [113]. This oversimplification results in the recovery rates being compromised which leads to the wasting of resources.

Finally, exploring the available hydrometallurgical techniques and the solvent pre-treatment methods, a gap and a potential improvement to the material recovery rates was identified. Solvent pre-treatment, in general and using DMSO in specific, show good improvements to the recovery rate of metals; however, their application with medium and fine sized particles was not investigated [80], [92], [93].

With these gaps in mind and guided by the knowledge acquired from the extensive literature review, potential solutions were explored which helped develop the research questions and the objectives of this research.

3.2. Research questions

The research questions which guide this research are divided under two main topics; the first is related to Decision Support Systems and the use of computational sustainability in tackling the WEEE problem (T1), while the second covers the in-depth study of one type of WEEE which is PCBs and the exploration of an optimized material recovery method (T2).

For T1, the research questions that this study aims to respond to are:

- R1: Is an ontology-based multi-domain DSS that covers the technology, material, and hazard domains a feasible and practical solution to simplifying the complexity of WEEE and improve the decision-making process for a circular economy?
- R2: How can such a DSS system be built ensuring its scalability and reusability without compromising the ease of use for non-expert users?

For the second part of the research (T2), the research questions defined are:

- R3: What is the extent of variation in material composition between the different PCB categories (motherboards, RAM, and CPU and chipsets), do these variations exist within the same category between the different models, and how can these variations impact resource recovery strategies?
- R4: How does solvent pre-treatment of motherboard PCBs using DMSO affect metal recovery rates and what is the extent of using finer particle size on the efficiency of material recovery?

These questions gave a clearer view of the objectives and the methodologies which can be used to realise this research.

3.3. Objectives

This research has the aim to bridge some of the previously highlighted gaps in the WEEE sector. To begin with, the research aims to develop a framework for an integrated DSS. The DSS would be ontology based and should bring together the disconnected domains of WEEE: technology, materials, and hazards. This objective would promote circular economy practices and enable efficient sustainable WEEE handling. This can be achieved and validated through focusing the scope of the DSS on solar PVs as an initial proof-of-concept (POC) and also to demonstrate the validity of the solution within the broader WEEE applications.

Furthermore, the developed DSS is intended to simplify the WEEE and ensure usability for non-experts, this can be achieved through an intuitive GUI design. In addition, the developed ontology which will act as the core of the DSS should be scalable and reusable guaranteeing the DSS's validity and adaptability for future expansion without major structural overhauls as the domain continuously evolves.

Regarding the enhanced understanding of WEEE, a focus is put on PCBs with an aim to characterize different categories of PCBs and understand the material variability, trends, and potential implications for tailored recycling strategies.

This study is rendered complete with the objective to benefit from the obtained data from the material characterization of PCBs in order to investigate the solvent pre-treatment using DMSO and identify the optimal particle size range for maximized improved recovery rates for critical metals such as copper.

3.4. Research methodology

To address the defined research questions and objectives, a mixture of experimental, quantitative, and secondary data analysis methods is implemented.

For the DSS development, an agile method is followed which allows for the continuous development, integration, and testing of the developed system. This agile method is combined with an extensive secondary data analysis to collect the needed data and populate the developed ontology. The secondary data analysis includes the mapping of WEEE categories and handling technologies, cataloguing the materials found in WEEE, both metals and non-metals, as well as the defining of the different toxicity profiles associated with the various materials and technologies. This comprehensive analysis combined with the Modular Ontology Modelling (MOMo) methodology will guide the development of the DSS and the ontology and guarantee the implemented work is aligned with the defined objectives. To validate and test the develop ontology, SPARQL queries are used to simulate the data extraction process of the DSS.

For the PCB characterization and treatment optimization, experimental and quantitative analysis is used. Various samples are collected and identified, then prepared for both the material characterization analysis using different methods such as XRF, ICP-OES and ICP-MS. The obtained data is then validated using cross verification of the results of the different analytical methods and a statistical analysis is used to calculate averages, standard deviations, and correlation coefficients to compare the different analysed models and PCB categories and unearth possible trends. The samples are also used for the investigation of the solvent pre-treatment technique against the different particle sizes and similar analytical methods are used to test for the optimized conditions and calculate recovery efficiency.

This methodology combines domain integration, data-driven precision through material analysis and practical optimization of one of the available pre-treatment methods with the goal to advance sustainable WEEE management.

Chapter 4

Building the Decision Support System

This ontology-based DSS is innovative in the way it integrates the knowledge from multiple domains while being scalable and expandable making it easier for non-domain experts to reach informed decisions. Unlike existing systems, this DSS addresses the technological, materials, and hazards domains all the while allowing for integration with other ontologies, such as those in the business and legislative domains, giving a more holistic perspective on WEEE management. Leveraging the ontology-based core, the DSS enables reasoning and the automatic derivation of relationships across various WEEE categories and aspects. This capability guarantees adaptability for future development of the ontology or its integration with ontologies from other fields.

Protégé and OWL language are utilized for building of this ontology [114], [115]. While Protégé offers tools accessing the ontology in XML format or as a graphical representation as well as supports data extraction, it is not intended to be used as the DSS's user interface. This is due to the need for advanced knowledge of the software and expertise in query languages, making it challenging for non-expert users which would give an adverse outcome to the intended simplification of the decision-making process.

4.1. DSS structure

The aim of a DSS is to simplify and support informed decision-making, this makes user-friendliness a critical requirement. To realise such requirement, it is essential before starting with the development process to establish clear objectives that align with the problem being addressed. In addition, the intended users, their nature and backgrounds, and the potential applications of the DSS have to be established. This ensures that the resulting system goes hand in hand with the intended objectives. For guidance in this regard, the methodology outlined in [96] and applied by [102] during the development of OntoSCS has been adopted, ensuring a precise definition of the key aspects of the ontology being developed and a well-organized design.

A DSS is generally composed of multiple layers; the DSS developed in this research includes three distinct interconnected layers. The foundational layer is the ontology, which works as the core of the system. This layer structures all data from the different domains and defines the relationships and interactions among them. The domains covered by the ontology must align with the objectives of the DSS and its intended applications; the broader the ontology the wider the scope of the DSS and the ability to integrate the current ontology with future ones from other domains enhances the usability and expandability of the DSS. The DSS currently focuses on three key domains that simplify decision-making and link the available data on WEEE. These domains not only address the objectives of the system but also facilitate a more comprehensive understanding by interconnecting crucial aspects of WEEE management. The domains align directly with the three pillars of sustainability. Specifically, the materials domain can be directly related to business models, providing insights onto the economic dimension of WEEE management through the quantification of the materials enclosed in the handled WEEE. The technological domain, being central to industrial operations gives an in-depth understanding of the treatment methods and conditions along with the process efficiency. This supports the decision-making process and drives corelations between the expected capital and operational costs and the foreseen profits adding more certainty to business models. Finally, the linking of various technologies, processes, and materials to their environmental and health impacts offers a comprehensive perspective on the sustainability of the proposed solutions. Integrating these three domains contributes directly to the streamlining of the decision-making process, and ensures decisions are informed by a complete understanding of the problem rather than a narrow, single-dimensional view.

Given that the primary goal of the DSS is to simplify the WEEE management domain, the top layer of the system is designed as a Graphical User Interface (GUI). This interface enables users to interact with the ontology at the base layer, submit inputs, and retrieve relevant information in an accessible and user-friendly format. The connection between the base layer and the GUI is facilitated by a querying and computational program. This program processes user inputs, establishes relationships between the various domains and categories within the ontology based on predefined links, and generates results. These results are then transmitted to the GUI for user representation. Figure 2 provides an illustrative overview of the DSS, outlining the roles of each layer and the interactions between them.

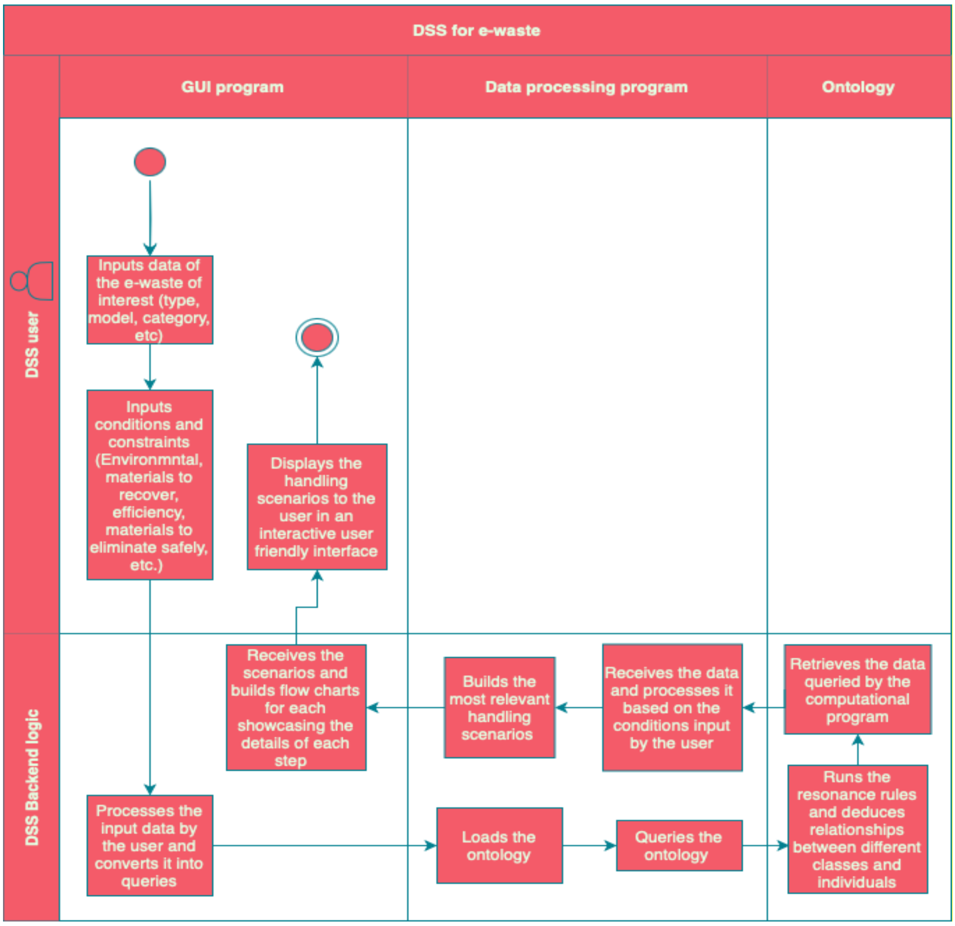


Figure 2. DSS structure and the interaction between the different DSS layers

4.1.1. Objectives, scope of the DSS and design methodology

The domain of WEEE encompasses discarded electronic and electrical devices that have reached their end-of-life phase or been disposed of by users. The classification of such waste varies across regulatory frameworks and guidelines. The E-waste Statistics Guidelines on Classification Reporting and Indicators presents a six-category taxonomy: Temperature exchange equipment, Screens and monitors, Lamps, Large equipment, Small equipment, and Telecommunication equipment [10]. The EU established the WEEE directive which uses a more comprehensive classification system that is widely acknowledged internationally. The directive delineates ten distinct categories of WEEE: Large household appliances, Small household appliances, IT and telecommunications equipment, Consumer equipment and photovoltaic panels, Lighting equipment, Electrical and electronic tools, Toys, Leisure and sports equipment, Medical devices, Monitoring and control instruments, and Automatic dispensers [5]. These frameworks, while useful, merely scratch the surface of the complexity inherent in WEEE management, as there are technological and material differences among the same category of WEEE. The heterogenous nature of WEEE materials further complicates the management process. Given the variation in material composition across different models and categories, a useful approach to building the DSS is by initially concentrating on a specific WEEE category or type. This enables the detailed modelling of not only the category but also the handling processes and their associated impacts before progressively expanding to include other categories. While the ultimate objective of the DSS is the comprehensive coverage of all WEEE types, the realisation of such an ambitious goal follows a phased methodology. This facilitates the iterative refinement of the DSS through continuous feedback, hence mitigating the complexities resolving impracticality that might arise from the simultaneous modelling of all WEEE categories at the same time. Such approach fosters the optimization of the system structure based on a systematic development supporting both expandability and scalability.

With this approach in mind, the presented ontology herein commences with solar PV systems management. This selection as a starting point was strategically informed by the projected trends which indicate significant growth in both the usage of solar PVs and their corresponding end-of-life waste generation [9]. The ontology was deliberately architected in order to accommodate the incorporation of complementary ontologies in addition to the expansion of the scope to encompass additional electronic waste categories and their respective treatment technique, hence fulfilling scalability requirements. Furthermore, this flexible structure ensures seamless integration of newly emerging solar PV treatment methods supporting the adaptability of the DSS to new technological advances and management techniques in the field.

To ensure a thorough understanding of the complexities of WEEE and the different realms it encompasses, the ontology covers three fundamental domains: treatment processes and techniques, potential hazards associated with both the materials and techniques applied and which impact the environment as well as human health, and finally the material composition with their respective classifications. The architecture of the ontology employs a deliberate level of abstraction, allowing components to remain generic for their potential reusage to model other categories. For instance, the concept of “metal housing” is generalized without tying it to solar PV applications, qualifying the same metal housing concept to be used in modelling a solar panel’s frame and equally represent a refrigerator’s exterior casing. Moreover, the defined reasoning rules embedded within the ontology gives the capability to automatically infer relationships between the defined components, establish correlations among different elements, and enhance the reusability of the ontology as it grows without affecting the structural integrity during scope expansion. This feature creates a robust yet flexible base which can adapt to the evolving nature of WEEE.

A comprehensive evaluation of existing ontologies revealed limitations in their potential application for the WEEE domain. While waste management ontologies such as OntoWM [116], and SWM-PnR [117] exist, their primary focus is on collection and monitoring phases making it less specialized for our WEEE ontology which takes a divergent path by focusing on urban mining and sound handling aspects, typically phases that follow the collection and monitoring phase. The architectural components of the DSS OntoWEDSS [118] offers potential adaptation value; however, its core domain, which specializes in wastewater treatment plant operations and microbiological processes, differs substantially from WEEE treatment techniques, thus limiting the reusability of the developed system. Another examined ontology is OntoCAPE [40]; an ontology which covers the chemical and process engineering domain.

While offering supporting modules for SI units and materials, the ontology operates at a level too abstract for practical WEEE management applications requiring extensive modification to its structure and modules in order to adapt it to the specific needs of WEEE rendering the adaptation process more complex than building a new ontology [112]. Limited modularity is another critical limitation that was observed in other existing waste management ontologies [99], this impedes the possible integration of these ontologies into a comprehensive WEEE management system. Given these constraints and the unique requirements of WEEE processing, the developing of a new tailored ontology emerged as the most practical approach to address the challenges of WEEE management effectively.

The development of the ontology follows an approach that is harmonized with the methodology of the overarching DSS unfolding through the precise definition of the objectives, use cases, and operational parameters. These elements, foundational to the development process, guide the ontology into emerging into a clear and functional ontology which satisfies the expected interaction mechanisms simplifying the navigation of the labyrinths of the WEEE management domain. From the thorough analysis of the system requirements, emerged the system objectives which address the fundamental questions regarding the necessity of this ontology and the queries it would respond to. The system is continuously assessed during its creation phase in order to evaluate the coverage of all needed entities within the scope of this ontology. This evaluation is further complemented by questioning the reusability of the ontology and that the clarity of the modelled entities using sufficient description and clear annotations enhancing the interoperability of the system. This methodological approach synthesizes two ontology development practices: the Modular Ontology Modeling (MOMo) methodology, particularly relevant for digital product passports [98], and the ontology lifecycle model focusing on micro-level development intricacies [96].

The ontology’s development primarily relies on secondary data sources across the three key domains: technologies, environmental and health impacts, and materials composition. However, a significant challenge was faced during the development process given the lack of precise data on the material content across various WEEE types and product models. To rectify this shortcoming, the quantification of material composition across diverse WEEE items was included in the objectives of this research. This objective is further fulfilled through the analysis of the obtained data with the aim to come up with a simplified procedure to address WEEE items of varying models and types belonging to the same category. The added research work enhances the DSS through the integration of primary precise data about the material composition, thus improving the processing accuracy. The studied WEEE items and the data obtained are discussed exhaustively in Chapter 5.

4.1.2. Potential users and use cases

The structure of the ontology covering the details of technical methods, materials content, and environmental and health impacts provide a holistic overview of WEEE management allowing a better understanding of the potential material recovery opportunities, structural description of the WEEE item and the most adequate treatment methods.

The DSS would feature an intuitive GUI accessible to any user regardless of their background, thus simplifying the usage of the DSS and eliminating the need of language engineers, domain experts, specialized knowledge in ontologies, or complex software operations in order to use the system. The system therefore caters to diverse stakeholders with potential users identified as decision-makers, policymakers, and business owners and investors exploring opportunities in WEEE management. The accessibility feature goes hand in hand with the objective of the DSS to provide easy access to WEEE knowledge and support informed decisions within a green circular economy.

A deeper dissection of the DSS shows the system's functionality revolves around three main use cases. When a user is presented with a specific WEEE item or category and is interested in learning more about its material content and the possible handling scenarios. The system generates comprehensive process flows detailing the material composition at the starting point and their recovery along the way. The process flow also showcases the treatment techniques and the associated impacts in addition to the needed equipment, operational parameters and any additional materials to be inputted into the system. The materials are quantified per kilogram of WEEE and temporal estimates for each step of the process flow is also shown. Additionally, the user can choose a specific component within the broader WEEE items. For instance, instead of looking at solar PVs as a whole the user can specify the housing of solar PVs and the system in return details the material composition and content as well as the recovery and handling methods highlighting the environmental and health implications. The third use case is material-centric, where the user is interested in a specific material or resource, such as rare-earth metals, and is looking into identifying the WEEE items with the highest concentrations of these materials in addition to those with the highest reported recovery rates. This is particularly targeted at urban mining initiatives, helping stakeholders pinpoint opportunities and foster material recovery from WEEE as the Critical Raw Materials Act dictates [37].

To address the aforementioned three use cases and satisfy the objective of simplifying the ontology usage eliminating the need for domain experts to use the DSS, an initial GUI consisting of three panels is designed. When fully developed, the interface will feature input selection tabs for each of the three use cases, a middle interactive flowchart displaying the processing scenarios and components, and a leftmost panel designed to display the detailed information about one of the nodes of the flow chart upon user selection. The central panel, upon the submission of the user inputs, will dynamically generate the interactive flowcharts displaying the various processing scenarios in a node-based interface enabling the user to explore the different pathways. The details panel would show general details about the process or specific technical details related to one of the nodes selected by the user, the details include the operational parameters, hazards, detailed material content, process recovery efficiency or used equipment. This intuitive design ensures comprehensive information access while maintaining the simplicity and user friendliness of the system. The initial design is shown in Figure 3. This is a conceptual design rather than a fully implemented GUI. The prototype serves to demonstrate the intended user interaction patterns and the functionalities of the DSS.

Figure 3. Snapshot of the GUI design for the DSS

4.2. Ontology structure

Protégé is a tool commonly used to develop ontologies [100], [104], [107], [109], [110]. It has the advantage of being both open source and developing the ontologies in OWL language [114], [115]. Furthermore, it supports the use of reasoners which using the added properties of objects and data, and the defined rules infer new connections between the entities of the ontology. The advantages of using Protégé continue even after the ontology is developed as it allows the exporting of the ontology in various programming languages making integration and interoperability of the ontology with other systems a more manageable task.

Given the advantages reported to the use of Protégé, it has been used in developing the ontology in question (RRID:SCR_003299, V5.5) [114], [115]. The first step of developing the ontology is finding a way to represent the three interconnected domains that fall within the scope of the DSS. Therefore, the ontology is divided into 7 main categories: Component, E-waste item, Hazard, Material, Process flow, Process input and Treatment. Since scalability is one of the aims of the developed ontology, the categories are quite generic allowing to cover more items and grow the ontology with time further supporting its potential integration with other ontologies that have a more focused objective on one of the domains covered by this ontology. The ontology uses a top-down structure that grows from general categories to specific details. The chosen categories fully cover the domains of interest; the technology area includes Process Flow, Process Input and Treatment categories, while the environmental and health risks fall under the Hazard category. The Material category addresses the material composition domain. Critical to the ontological architecture are the Component and E-waste item categories, which serve as building blocks for modelling various WEEE classifications and their constituent parts. This systematic categorization enables seamless integration of new elements while maintaining structural integrity and logical relationships throughout the ontological hierarchy.

The design's expandable nature permits detailed elaboration within each category, allowing for the incorporation of emerging technologies, newly identified hazards, or novel material compositions. This adaptive methodology ensures the ontology remains current and comprehensive while preserving its structural integrity and practical utility for WEEE management applications. In addition, it facilitates the reusability of the items defined under each category for cross functional usage especially when modelling scenarios or waste items which might partially share a procedure or a component.

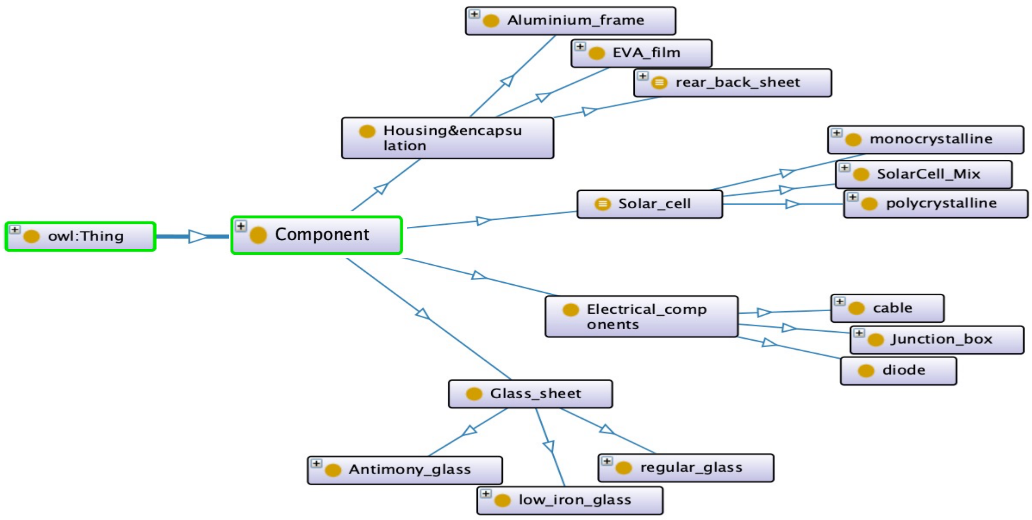
4.2.1. Classes

Classes are the fundamental organizational units in an ontology, made up of a hierarchical structure through parent-child relationships. Each class can hold several subclasses, as needed, creating increasingly specific categorizations as one moves deeper into the taxonomic structure. This hierarchy supports the scalability of an ontology by allowing the progressive specialization of concepts [96].

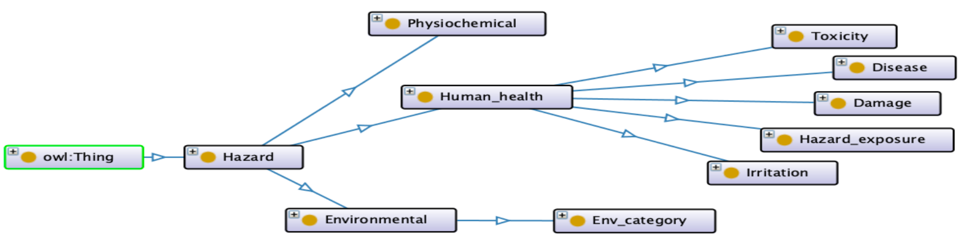
In the currently developed ontology, solar PV systems are prioritized as the initial WEEE category for modelling. The choice represents the starting point of the ontology as a proof of concept (POC) through establishing the structural foundation while maintaining the flexibility to incorporate additional WEEE categories, treatment technologies, hazards, and components subsequently. Some broader concepts and data elements, particularly within the materials and treatment classes, were added to the ontology anticipating future expansion requirements. The created classes and subclasses under each of the aforementioned categories are shown in Table 5. The shown snapshots from the ontology class hierarchy employ visual representation through connecting lines shown in blue to illustrate relationships between entities. For instance, within the Component category, an Aluminium_frame exists as a subclass of Housing&encapsulation, which in turn functions as a subclass of Component.

Table 5. Classes defined within the WEEE ontology (with reference to solar PV)

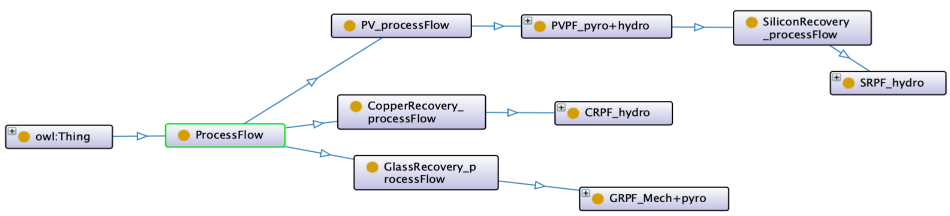
<table>
<tr><th>Category</th><th>Description</th></tr>
<tr><td>E-waste item</td><td>This is the starting point of the ontology under which the different WEEE types are defined. E-waste items would then be built from the defined components.</td></tr>
<tr><td>Component</td><td>Contains the various components that constitute the different types of WEEE ranging from frames and protective layers to electrical components.



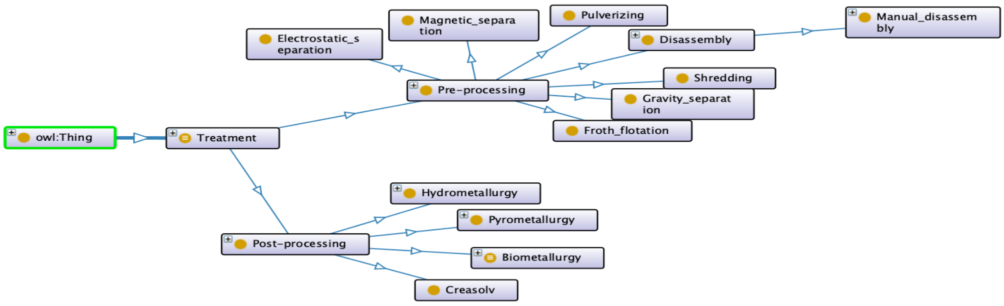
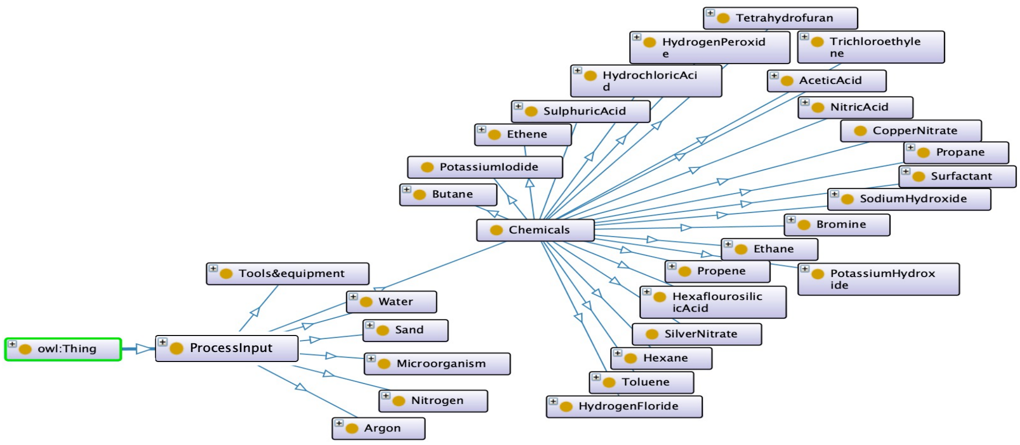
</td></tr>
<tr><td>Hazard</td><td>Risks and impacts of processes, items or materials are defined under this category. This includes both human-related and environmental jeopardies.



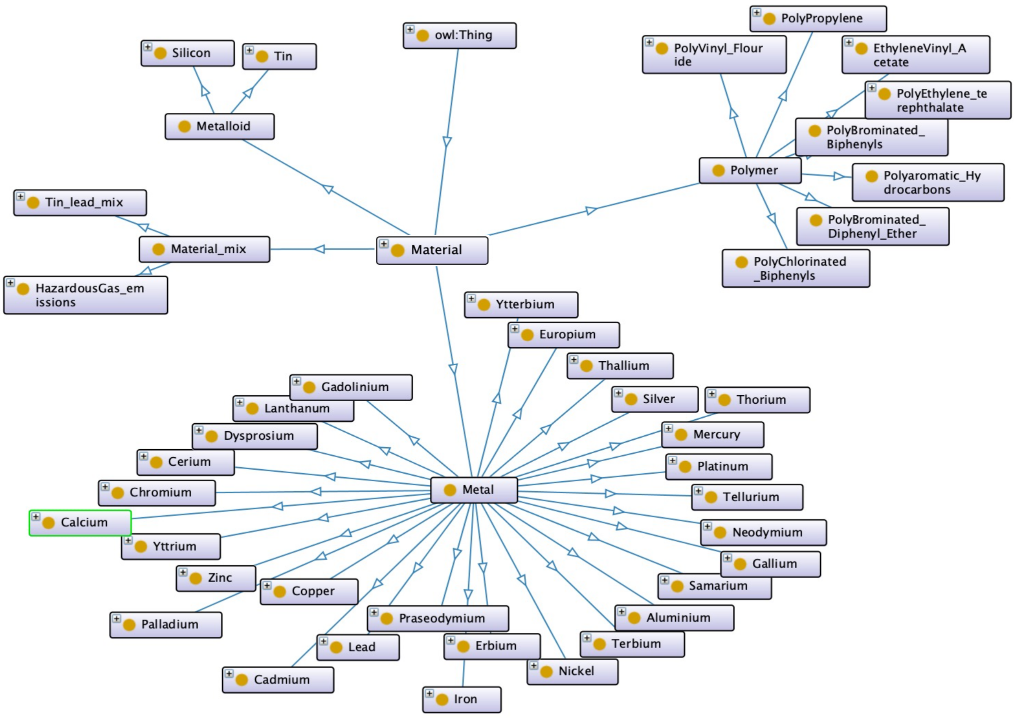
</td></tr>
<tr><td>Process flow</td><td>Any set of procedures or a treatment protocol followed during the handling process of WEEE is found under this category. One process flow can be composed of other subprocesses under the same category.



</td></tr>
</table>

Treatment	This category is focused on dealing with WEEE. A treatment method is a building block to process flows. 
Process input	For each handling process, a native input is one or more of the e-waste item components. However, other added inputs that are not part of the components can be found here. This includes tools, equipment, and materials. 
Material	The various types of materials that are used to construct the components are defined here. Noteworthy is the addition of some materials (rare and precious metals) that are not contained in Solar PVs since they were deemed useful in the subsequent phase of modelling other WEEE items

such as Printed Circuit Boards.



4.2.2. Object and Data properties

In an ontology, classes are containers of individuals (as further explained in the following section), which are specific instances of that class and inherent its defined properties. Across the ontology, the individuals can establish connections with other individuals regardless of their class through object properties. Individuals also use data properties to assign specific values to individual characteristics [96].

Both the object and data property structure are designed with flexibility and scalability in mind, catering to even the mildest differences for a more detailed and sophisticated modelling. This idea can be seen in several seemingly similar terms. For instance, while "recover" and "remove" might appear repetitive, they serve distinct purposes in the process modelling. "Recover" indicates material collection for future use, as in hydrometallurgical processes that collect valuable metals. Conversely, "remove" signifies material elimination without reclamation, such as in processes eliminating hazardous lead where the material is no loner of interest. The term "output" adds another layer, describing material production that requires additional processing steps in order to reach the level of being recovered.

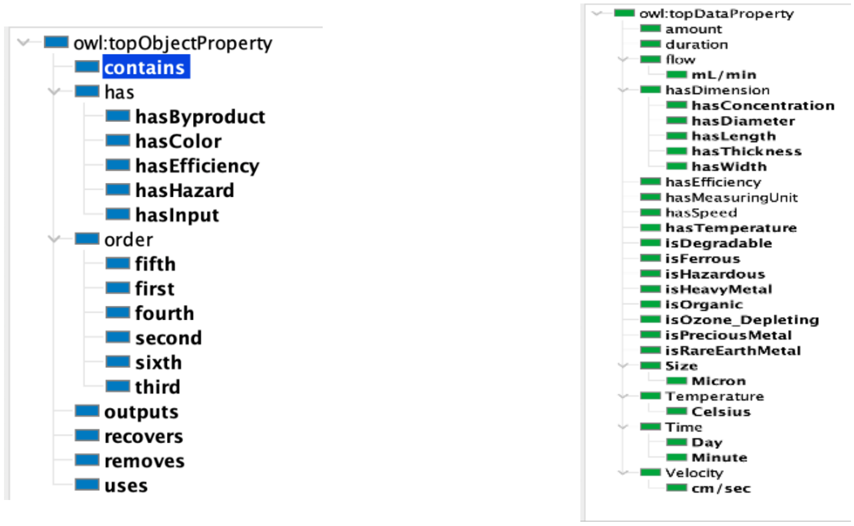
Another example of the ontology's flexible structure is the "order" property used in defining the sequence with which a treatment process is executed. This property has hierarchical sub-properties: "first", "second", "third", and so forth. While the sub-properties currently extend to the sixth order, this structure allows seamless addition of further steps in case of need, demonstrating the ontology's inherent expandability. This sequential organization enables precise process documentation while maintaining flexibility for future expansion.

The flexibility is not only enshrined within the structure of object and data properties, but it also extends to the list of properties defined for both. The approach to hazard documentation manifests this philosophy where the system employs both "hasHazard" as an object property and "isHazardous" as a data property. This dual-property system accommodates varying documentation needs from detailed hazard specification connecting it to the associated hazards (hasHazard) to simple hazard flagging (isHazardous), providing flexibility in how hazards are recorded and tracked within the system.

Similar seemingly redundant occurrences are deliberately structured in order to serve the strategic purpose of allowing multiple modelling approaches and accommodating varying levels of complexity based on the available knowledge and the level of interest. This architectural approach ensures the ontology can evolve while maintaining consistent relationship definitions. The hierarchical property organization facilitates easy expansion, while flexible relationship definitions accommodate new connections as the ontology grows. Through these layered modelling capabilities, the system supports increasingly complex requirements while maintaining its fundamental structure and usability. The lists of defined object and data properties for the WEEE ontology are shown in Figure 4(a) and (b) respectively.

4.2.3. Individuals and annotations

In an ontology, individuals represent the terminal nodes, serving as specific instantiations of their parent classes. These distinct instances express particular cases within the class hierarchy. To better explain the concept, the class "Process Input" can be taken as an example. The class contains the subclass "Acetic acid" which has several individuals instantiated representing discrete acetic acid concentrations. The visualization of such hierarchy can be seen in Figure 5.



(a) **(b)**

Figure 4. (a) List of object properties added to the ontology and used to draw relations among the different class individuals; (b) List of data properties added to the ontology to describe the class individuals

The inherent complexity of these relationships and the profound hierarchy render the meticulous documentation of individual entities paramount. The detailed characterization ensures both the conceptual clarity and precise modelling of relationships and interactions between the instances and classes of the ontological model. To support this level of descriptive precision, three types of annotations were introduced in the WEEE ontology:

1. Reference: document the scholarly sources underpinning the information
2. Symbol: an annotation added to individuals of materials and chemicals to provide their chemical formulae
3. Comment: captures supplementary information relevant to the entity

The annotation framework is exemplified in Figure 5 and Figure 6, where the latter demonstrates the detailed characterization of the individual "Hydro+thermal_reclamPV1" using these descriptive mechanisms. Such comprehensive and exhaustive annotation practices enhance the ontology's utility by avoiding ambiguous interpretations and providing accurate modelling of the ontological elements and the interactions among one another.

The systematic application of these annotations creates a solid foundation for knowledge representation supporting the precise documentation of relationships and properties without compromising the clarity and scalability of the ontology. This approach ensures that each individual entity is associated with all the needed information to thoroughly describe it and properly contextualize it within the broader domain of WEEE.

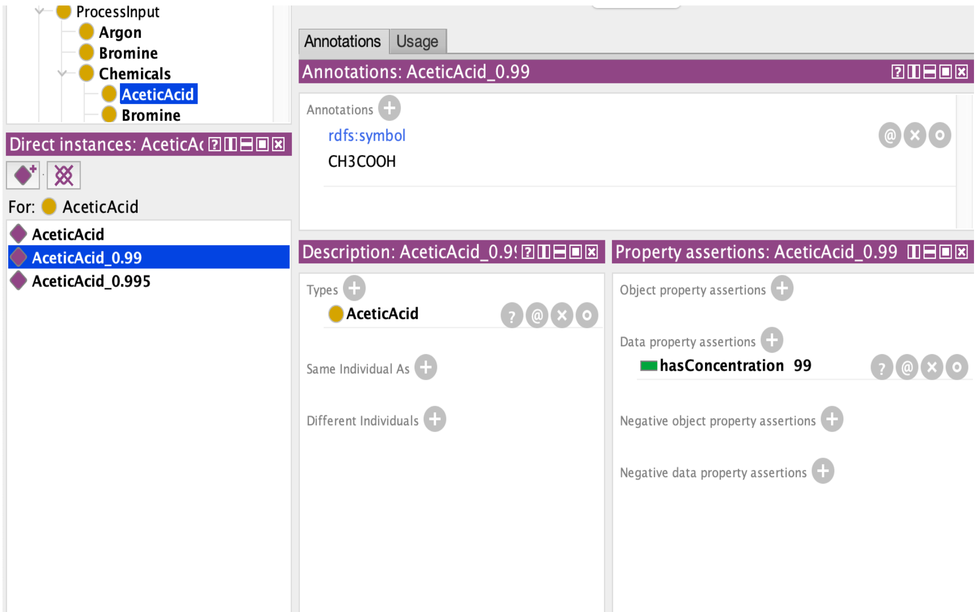


Figure 5. A screenshot of one of the subclasses in the ontology showcasing the created individuals of Acetic acid with various concentrations and their distinct representation within the ontology

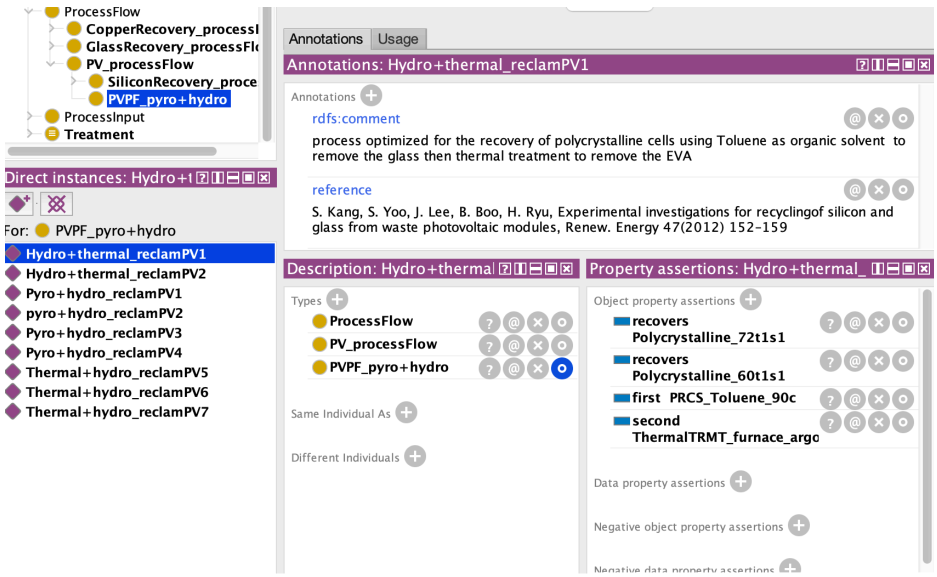


Figure 6. A snap from the ontology demonstrating the use of annotations in modelling individuals

Exploring the individuals created within this ontology reveals the modelling structure for WEEE items and their constituent components particularly focused on solar PV systems. Dissecting the various components found in Figure 7, which is a snapshot of the ontology developed using Protégé, demonstrates the usage of the ontology while highlighting its sophisticated yet flexible structure. In the center of the figure the individual “SolarPV_c-Si_Mix_T1”, classified under the “e-waste item” class, represents a mixture of different solar PV types. This mixture is modelled through the individual “SolarCell_mix” which is made up of several individuals representing distinct instances of solar PV types, such as monocrystalline, polycrystalline, and cast monocrystalline cells. Each of these constituting individuals is characterized by a variation in size or the number of cells per panel. The "SolarCell_mix" individual is an instant of the subclass having the same name "SolarCell_mix" where the latter is a subclass of "Solar_cell" falling under the broader "Components" category. The complexity of the model and the entangled relationships between the various entities is further demonstrated when examining the subclass "Glass_sheet"; which although belongs to the same category of "Components" is also a direct constituent of the "SolarPV_c-Si_Mix_T1" individual through the subset individual "antimony_glass_0.01-1". The "antimony_glass_0.01-1" belongs to the "Glass_sheet" class by being an individual of the subclass "Antimony_glass". The "0.01-1" in the nomenclature of the in "antimony_glass_0.01-1" individual refers to the antimony percentage present per kilogram of glass. In the center-top section of Figure 7 the individual "TinLead_mix1" is found as another constituent of the "SolarPV_c-Si_Mix_T1" instance, the individual models the combination of tin and lead reported in the dissecting of solar PV mix in [119] without specifying the exact component housing these materials. This demonstrates the adaptability and flexibility of the ontological system to the different modelling approaches and the potential ambiguity found in the literature, enabling the system to overcome this vagueness and model the solar PV system without the need to radical changes to the ontological structure. Tracing the individuals and classes which make up the aforementioned instance "TinLead_mix1" leads to the individual "Lead" to which three other individuals are linked using the relationship "hasHazard" referring to the three hazards – acute toxicity ingestion, and inhalation. Similarly, trailing other individuals and classes in Figure 7 reveals the other components present in the individual "SolarPV_c-Si_Mix_T1" and their subsequent relations with other components, classes, and individuals.

A similar approach is used in the modelling of the handling and treatment techniques where specific individuals were developed representing each step in the process. These steps are subsequently detailed using annotations, object properties, and data properties. The modelling technique is demonstrated in Figure 8 which shows the structure of a multistage treatment process for solar PVs. The process removes the encapsulation layers like Ethyl vinyl acetate (EVA) and TedLar using a thermal treatment with a subsequent hydrometallurgical process to recover silicon and copper utilising various acids [120].

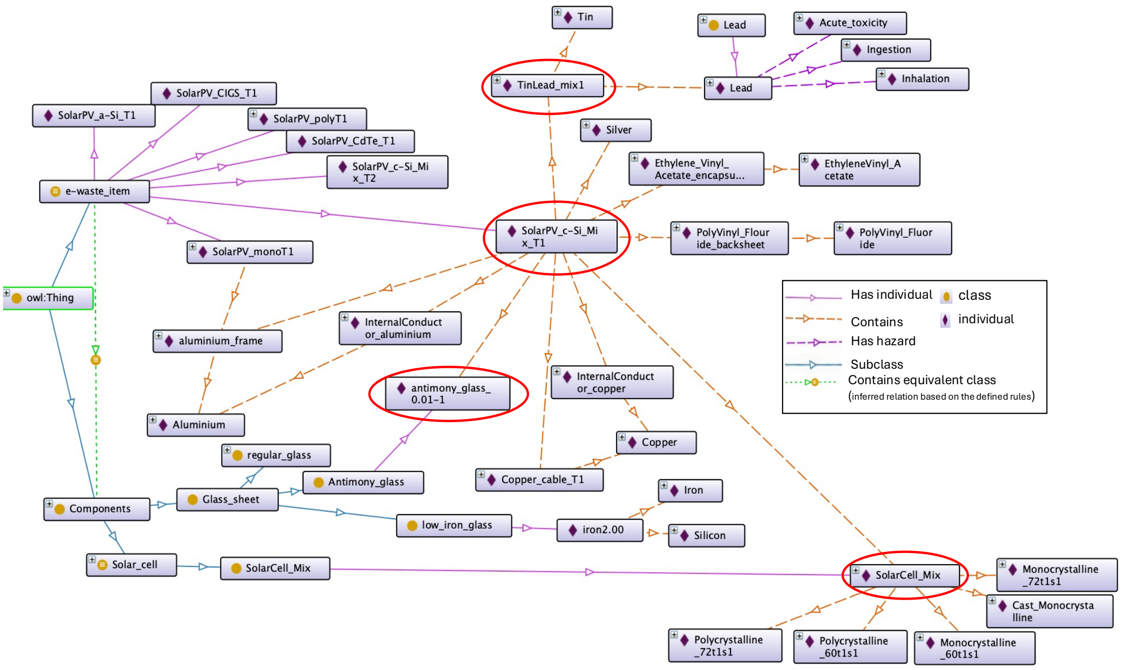


Figure 7. An example to modelling a mixture of solar PVs made up of different solar cell types

The multistage treatment process is represented by the individual "Thermal+hydro_reclamPV7" shown in the far-right section of Figure 8. The individual is classified under the "ProcessFlow" class through the subclasses "PV_processFlow" and "PVPF_pyro+hydro". These two subclasses are meant to categorize the process flows into specific ones for solar PVs, hence the prefix "PV" and subsequently according to the technology used, thus the name "pyro+hydro". Other more specific processes for material recovery can be found such as the subclass "SiliconRecovery_processFlow" which also follows the same taxonomy and classifies the subsequent processes based on the technology used.

Back to the individual "Thermal+hydro_reclamPV7", the process is linked to the

"Components" class using the "recovers" relationship, connecting it to the various types of solar PV cells it can process; specifically polycrystalline, monocrystalline, and cast monocrystalline cells of different dimensions. Thus, the cells, which are categorized as components, are recovered through this process. Another important part of the modelled process is how it is connected to the "Treatment" class with its two child classes "Pyrometallurgy" and "Hydrometallurgy". The different individual pyro and hydrometallurgical processes are connected to the "Thermal+hydro_reclamPV7" process using the previously discussed "order" property which has the sub properties "First" through "Fifth" specifying the exact step sequence through the dotted color-coded arrows helping to breakdown the treatment process while maintaining clarity and avoiding confusion. For example, the individual "ThermalTRMT_furnace_330c", belonging to the "Pyrometallurgy" subclass, is the first treatment stage, while, based on the legend of the color-coded arrows, the fifth and last stage is the individual "PRCS_SodiumHydroxide_25". The latter belonging to the "Hydrometallurgy" subclass of "Treatment" and is a process that uses Sodium hydroxide at 25% concentration to remove the P-N junction [120]. A more detailed view of the entire multistage treatment process is shown Figure 9 specifying the treatment sequence, the processes used, and the components recovered.

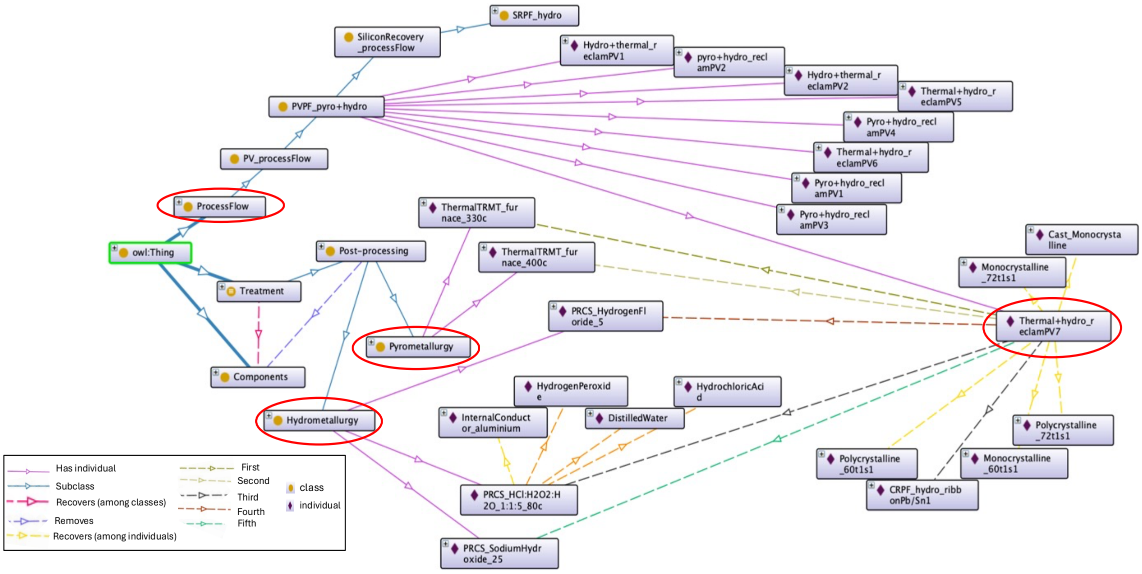


Figure 8. An illustration of the modelling of a treatment process for the recovery of solar PV

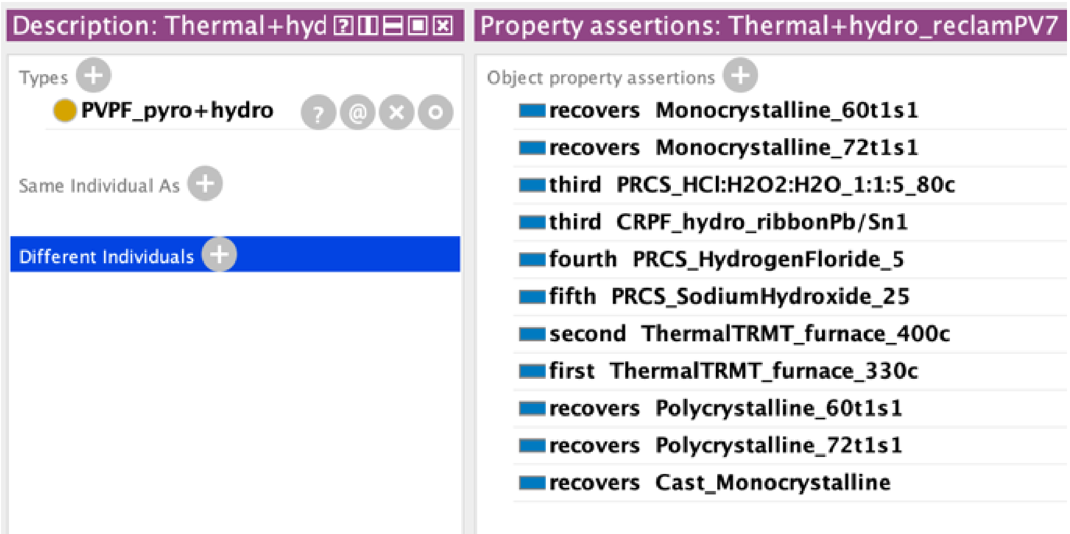


Figure 9. A detailed view the internal structure of the treatment process individual "Thermal+hydro_reclamPV7"

4.2.4. Rules and Reasoning

Ontologies excel in their ability to infer relationships connecting classes and individuals implicitly and explicitly. The key to this functionality is a reasoning engine with reasoning rules that are defined by the ontology creator acting as guidelines to the reasoner ensuring the inferred relationships are correct and do not affect the structural integrity of the ontology. The reasoning engine incorporated for this task in the WEEE ontology is HermiT (RRID:SCR_016006, V1.4.3.456) and SWRL to define the rules [121].

The implemented rules in the context of the WEEE ontology serve two primary purposes: they track the potential hazards and impacts associated with various components, processes, and materials, while also providing enhanced clarity regarding process outcomes.

Figure 10 illustrates the key rules defined, beginning with the Hazard Transfer Rule, which establishes that when a process utilizes a material with a known hazard, the process inherits that hazard classification. The second rule links hazards to processes based on the hazardous properties of their byproducts, while the third creates connections between process hazards and the hazardous materials involved in the process. The fourth rule associates hazards with specific treatment steps when hazardous materials are present in those steps, and the fifth establishes links between e-waste items and their material content based on the components they contain. The final three rules focus on material recovery and removal processes, establishing logical connections between treatment steps and their outcomes.

These rules, as depicted in Figure 10, create a comprehensive framework that bridges the three core domains of the DSS: materials, hazards, and treatment technologies. Among the rules defined in Figure 10 is the first rule which states that any process acquires the hazard type which is associated with one of the materials that same process uses. The same logic is applied to the second, third and fourth rules which associate hazards to the processes which contain or produce as a byproduct the hazardous material. A similar approach is used to automatically associate the materials contained in an item with the processes which handle these items.

This rule-based system creates an interconnected network of relationships that enhances the ontology's ability to support decision-making processes by automatically identifying and mapping relevant connections across these domains. The implementation of these rules ensures a more thorough understanding of the relationships between materials, their associated risks, and appropriate treatment methodologies.

```
hasHazard(?material, ?hazard) ^ uses(?process, ?material) -> hasHazard(?process, ?hazard)
hasHazard(?material, ?hazard) ^ hasByproduct(?process, ?material) -> hasHazard(?process, ?hazard)
hasHazard(?material, ?hazard) ^ contains(?process, ?material) -> hasHazard(?process, ?hazard)
hasHazard(?material, ?hazard) ^ order(?process, ?material) -> hasHazard(?process, ?hazard)
contains(?item, ?component) ^ contains(?component, ?material) -> contains(?item, ?material)
recovers(?process, ?component) ^ contains(?component, ?material) -> recovers(?process, ?material)
recovers(?treatment, ?material) ^ order(?process, ?treatment) -> recovers(?process, ?material)
removes(?treatment, ?material) ^ order(?process, ?treatment) -> removes(?process, ?material)
```

Figure 10. The guidelines defined for the reasoner as SWRL rules for the inference of relations in the WEEE ontology

4.3. Validation of the ontological model

After successfully modelling the WEEE domain and incorporating the previously defined scope of the DSS as well as extracting the various solar PV treatment processes from the literature arrives the validation phase of the ontology. To address the primary research question regarding the feasibility of developing a comprehensive system for the WEEE domain, the logical relationships established between the different classes and individuals within the ontology have to be validated after the execution of the reasoner.

The execution of the reasoner resulted in the expansion of the ontology through the establishment of new relationships between the entities based on the reasoning rules. Figure 11 shows an example of the inferred connections, highlighted in yellow, that were deduced by the reasoner for the individual "Hydro+thermal_reclamPV2", a process flow designed for panel reclamation. The reasoner's logical deductions established that the process inherently recovers silicon given its capability to recover polycrystalline PV, ascertained by the fact that the material composition of the "polycrystalline" object is silicon. Similar logical inference applies to the removal of EVA. Furthermore, the reasoner classified the process as both pre-processing and post-processing treatment, depending on its sequential position within the complete handling procedure. These logical inferences were derived from the established entity relationships and guided by the rules previously elaborated in section 4.2.4. while the reasoner-inferred relationships operate on an ontological level, they effectively reveal the robustness of the DSS and validate the efficacy of this modelling approach in connecting three traditionally disconnected domains [23]. The derived relationships illustrated in Figure 11 provide a comprehensive process overview despite the absence of the developed GUI layer, thus indicating the substantial potential of a fully developed DSS.

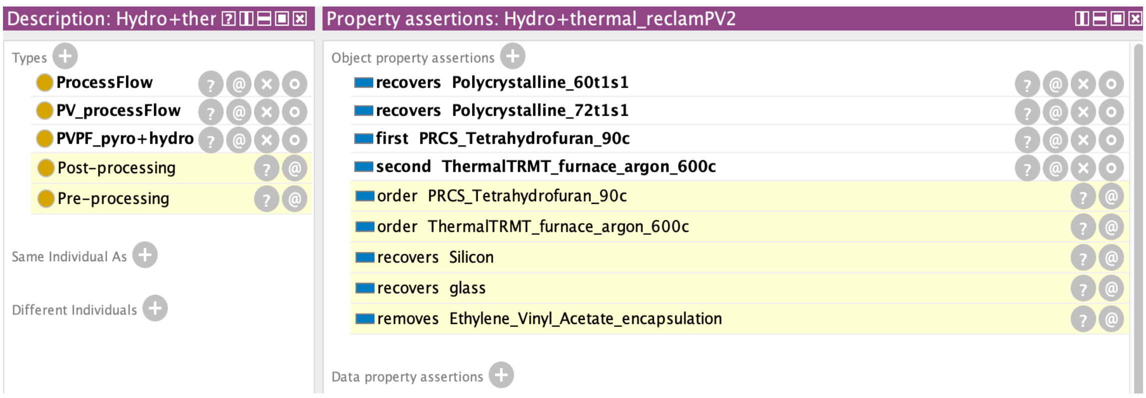
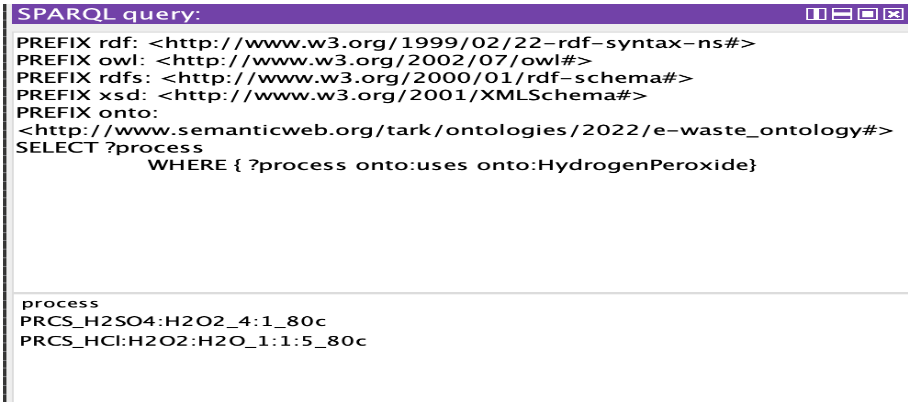


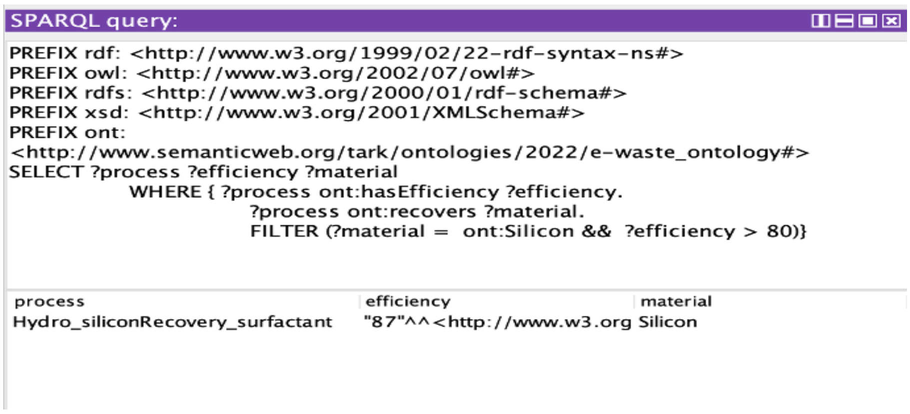
Figure 11. An example of the inferred relations among classes and individuals using the HermiT reasoner

Another validation method for the ontological model and its capabilities is through the SPARQL querying functionality that Protégé software also supports. SPARQL functionality enables the direct interaction with the ontology through the Protégé interface without requiring additional software development or integration; in addition, it functions in a comparable manner to traditional database querying languages such as SQL [96]. On the downside, the implementation of SPARQL necessitates specialized knowledge of the language and syntax and is not optimised for non-expert users, yet its application in this context served merely the model validation rather than as a user interface component.

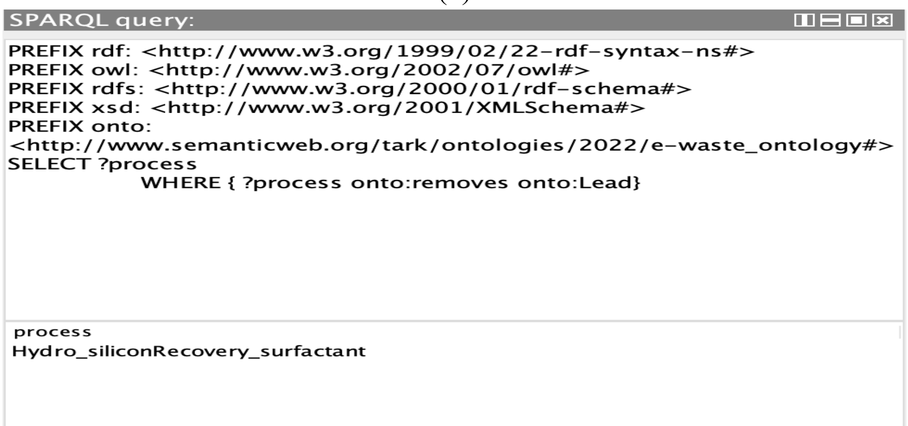
The first research question related to the DSS could be validated through the execution of SPARQL queries and subsequently analysing the results. Three different queries were applied and are demonstrated along with their results in Figure 12. The first query targets the various processes that utilize hydrogen peroxide in the chemical treatment process; the list of results obtained correspond correctly to the defined process. Queries can cover a wide spectrum ranging from broad searches such as the listing of processes that use a specific chemical agent as in the first query also shown in Figure 12 (a), or the material removal capabilities of a process such as the query in Figure 12 (c) which examines processes that remove lead. Such simple queries can be used when doing a preliminary or exploratory search to find grasp an understanding of the topic. More sophisticated queries incorporating multiple conditions and constraints can also be used for more specific and targeted solutions satisfying a decision-maker's preferences based on given regulations and constraints. Such an example can be seen in Figure 12 (b) which specifically targets process recovering silicon with efficiency exceeding 80%. The query results and reasoner-derived relationships aligned with expected outcomes, with no anomalies detected. While these queries represent basic implementations, they effectively demonstrate the capacity to consolidate the WEEE domain into a holistic system addressing various sustainability aspects. Referencing the DSS logic flow diagram presented in Figure 2, the exemplified data extractions in Figure 12 represents the ontological data retrieval phase. Upon the complete DSS implementation, this extracted data would undergo processing for presentation through an interactive GUI, providing not only the process name but also comprehensive process information including procedural steps, operational conditions, and associated hazards and impact which are all data already defined within the entities of the ontology. This functionality can be achieved through sequential queries, each building upon previous results to systematically reveal additional layers of the argument of interest, ultimately providing a comprehensive informational overview.



(a)



(b)



(c)

Figure 12. SPARQL query results (a) from querying the treatment processes which use hydrogen peroxide; (b) from querying processes that have a material recovery of silicon at an efficiency of at least 80%; (c) from querying the processes which help remove lead

4.4. Discussion

The effectiveness of the adopted DSS methodology is validated by the outcomes of the developed ontology. The methodology's initial phase, which focused on defining the objectives and use cases, has been mirrored in the functional operations that can be performed by the ontology satisfying these defined goals and cases. A primary goal of the DSS was to provide a simplified yet comprehensive representation of the WEEE domain; a domain that is commonly approached with a single field perspective even though it is transactional and spans multiple domains. The ontology accomplishes this primary goal by creating interconnections between the three domains of interest from a sustainability point of view. These relationships integrate all three domains under the single realm of WEEE management and articulate a less biased and more inclusive overview of a field challenged by the lack of a holistic outlook towards its constituent topics [23]. It also provides an easy access to the data in order to support a more informed decision and debunk misconceptions and biases in the WEEE field that might arise from a narrow viewpoint on the subject.

Next, the methodology evaluates the completeness of the scope of the ontology through assessing the constituent entities and their ability to represent the WEEE domain fully. As shown in the previously discussed examples taken from the ontology demonstrating the implemented structure with its sophisticated multilayered classes, embedded annotations, and object and data properties, the configuration is highly effective and detailed. It transcends the complexity of the WEEE and modestly presents the diverse processes across technological, material, and hazard dimensions in a somewhat intuitive manner. The taxonomy's flexible architecture facilitates the seamless and effortless expansion of the ontology during and post development, readily accommodating new technologies and emerging concepts and concerns as they arise. All three target domains were successfully encompassed by the classes allowing the desired level of detail for each class and topic; moreover, the object and data properties enabled straightforward entity relationships within the ontology. The effectiveness of the structure and its extensiveness was further validated during the data extraction phase, where SPARQL queries evidenced the efficiency of the taxonomy in retrieving information across all three domains within the ontology's scope highlighting their interconnectivity and the jigsaw integration of the ontology.

The findings from this research strongly support the conclusion that the developed ontology is both scalable and reusable. Hence, the extension of its application beyond solar PVs to other WEEE items can be achieved with significant flexibility. The ontology is versatile in its scope of application given its scalability that is rooted in the modular design, which divides each domain into small, manageable building blocks. These blocks can be combined and adapted to model a wide range of scenarios. A simple example for this versatility would be the "component" category which contains foundational elements used to model solar PVs. The reusability of these subcategory elements is demonstrated when applied to other WEEE items such as mobile phones or display screens. These devices can be modelled using already defined components like "housing&encapsulation," "Glass_sheet," and "Electrical_components", since they share the same features such as external housings, glass screens, and diodes, wires and other electrical components. In cases where new components are required, they can either be added under the existing classifications or created as entirely new entities depending on how these new components fit within the current taxonomy; however, the existing layout of the ontology would effortlessly and easily allow both operations since the taxonomy is abstract yet detailed oriented.

Another advantage of this design is the automatic inheritance of previously defined properties. Since reused components are already modelled with materials and hazards readily associated during the earlier development phases of the ontology, it eliminates the need for relationships to be manually re-established. Similarly, when new components are defined and linked to pre-existing materials in the ontology during the modelling process, the reasoning engine ensures that these components automatically inherit the corresponding hazards of materials. In this manner, the functionality has the two-fold benefit of significantly reduces the time and effort required to expand the system while maintaining its coherence and ensuring the holistic approach established in modelling WEEE in this DSS. Needless to say, the inherent reusability is not exclusive to the "component" category but is equally applicable to other classes such as "treatment" and "Process_input" along with their related individuals. This reiterates the framework's ability to easily accommodate the broad umbrella of WEEE items and associated process without compromising its structure or functionality.

The primary research objectives, simplifying WEEE decision-making and providing a holistic interconnected view of the WEEE sector, are fulfilled by the ontology as discussed in the previous examples and validations. First, with the help of the ontology the extraction of critical data becomes an easy task, which offers a comprehensive overview of WEEE streams and enables the identification of optimised management approaches. In addition, the system bridges the gaps between knowledge and practice through the integration of domains that are traditionally viewed as separate, such as materials, processes and environmental hazards. Furthermore, the practicality of the chosen methodology is underscored by the seamless integration across domains which also demonstrates the system's scalability and adaptability to evolving waste management challenges.

Based on this, the outcomes from this research accurately address the original research questions by helping to validate the taken approach in addition to delivering a structured foundation ready for further development. It can be claimed that the developed ontology has proven its potential as a vital tool for WEEE management; this is realised through a scalable, reusable, and efficient framework which supports informed decision-making while addressing the complexities of sustainability.

As the ontology expands to incorporate additional WEEE items there is a need for further validation of the functionalities to ensure accuracy and usability. To address this need, extra validation will be applied by comparing the results of experimentally implemented processes with the expected outcomes predicted by the model. This comparative analysis would accurately identify any discrepancies between modelled and real-world outcomes which acts as an overall assessment of the accuracy of the DSS. Such validation would not only confirm the reliability of the data provided by the DSS but also evaluate whether the modelled processes include sufficient detail for direct application without the need for further research on operational conditions and associated risks. Achieving this level of precision would fulfil the primary objective of the DSS: to consolidate and make knowledge about WEEE accessible and actionable for informed decision-making.

Among the faced difficulties during the development of the WEEE ontology is the data collection and modelling. Since extracting the relevant data from the endless literature is labour-intensive and time consuming. A process that starts by identifying the suitable sources then the extraction of the detailed data and its analysis arriving finally to integrating the data into the ontological model. Expanding the ontology to encompass broader range of WEEE items or even the greater ambition to cover different types of waste beyond WEEE would automatically translate into a significant increase in the required time and human resources. It can be argued that the effort put into such work is highly justifiable given that the extraction and modelling process is a one-time job that does not require being repeated routinely.

One way to overcome this challenge is by using artificial intelligence (AI). Since a time-consuming process such as the identification and extraction of relevant data can be efficiently automated using AI. This integration would also contribute to better coverage of the reported literature in addition to minimizing the risk of human error and helping identify and resolve data redundancies. However, the use of AI systems does not render domain experts obsolete as they would still play a critical role in verifying and refining the data to ensure its accuracy even after automation at least during the initial stages, until the AI system is sufficiently trained to handle complex domain-specific tasks with minimal oversight.

Another identified hurdle is the lack of precise data regarding the material composition of WEEE components. The gap in detailed data limits the development of a fully holistic ontology capable of providing detailed and accurate information for DSS applications or other uses. The data available in the literature is often generic rather than being specific to individual models. Most data reported in the literature relies on estimates of the material composition, resulting in only high-level categories being under the spotlight without further addressing potential variations across different models or subtypes of similar components. One of the arguments often overlooked is whether components that share the same functionality but differ in design or manufacturing origin exhibit significant differences in material content. The generalization approach followed in literature results in significant discrepancies between the actual composition of specific models and the generic data, which typically categorizes WEEE items into broad, uniform groups. In order to counter the impact of this gap more detailed and standardized reporting of material data is required greatly benefiting the development of comprehensive and accurate ontological models. The topic of data availability and precision within the WEEE sector is discussed profoundly in Chapter 5.

4.5. Conclusion

The significance of a WEEE ontology has been well demonstrated by the results presented in this chapter. The results showcase the WEEE ontology as a foundational step toward developing a DSS for WEEE management. It addresses the critical gap in the WEEE domain and overcomes its complexities by providing an accessible system tailored for non-expert stakeholders in an organized and scalable framework.

The ontology supports continuous updates and integration with other projects and ontologies making it adaptable to the evolving nature of the WEEE sector. The findings demonstrate its scalability and the reusability of its defined entities, making it highly versatile for future applications. The incorporation of a reasoner and the definition of logical rules further enhance the ontology's capacity to autonomously establish connections across the three core domains of interest—technology, materials, and hazards—underscoring its utility as a robust tool for knowledge representation and decision-making.

Data extraction, a vital operation within the DSS logic, was effectively demonstrated through SPARQL queries executed in Protégé. This simulation of the query phase, which would be automated in the DSS backend upon full development, showcases the ontology's ability to retrieve structured data to support informed decision-making. The development methodology, adapted from MOMo methodology [98] and the framework defined by [96], provided a guideline to designing effectively the DSS and ontology, and ensure its efficiency while addressing the defined gaps. This structured approach meets the defined scope of the DSS to bridge the three domains of interest while ensuring the scalability and reusability of the ontology regardless of the complexity of the subject. In doing so, the DSS aims to facilitate access to WEEE data, improve decision-making processes, and enhance overall management of WEEE.

While effective, the development process also revealed certain limitations. One of the primary challenges is the extensive time required for manual data extraction from the literature, aggravated with the lack of precise data on the material composition of various WEEE items and models. Addressing this gap is essential for streamlining end-of-life handling of WEEE and maximizing its resource potential. This limitation has already inspired the research further discussed in Chapter 5 and aimed at quantifying the material composition of different PCB types and models, with the ultimate goal of enriching the ontology with more accurate and detailed data as well as supporting the WEEE handling community.

Looking forward at the completed ontology with the incorporation of additional types of WEEE and complemented by the user-friendly GUI the effectiveness of the DSS is anticipated to be significantly enhanced. Such a system has the potential to support more informed decision-making and simplify urban mining processes, directly contributing to sustainable waste management practices. By aligning with the UN SDGs [122], the DSS would promote responsible consumption and production, help mitigate climate change, foster new industries, and improve solid waste infrastructure. Implicitly, these contributions would support economic growth, public health, and overall well-being.

The ontology itself holds standalone potential beyond its integration within the DSS. Experts familiar with ontology tools like Protégé can leverage it independently to extract valuable data and inform decision-making processes. Additionally, future integration of AI offers exciting opportunities to further enhance the ontology. Incorporating AI could streamline updates, improve data integration from other ontologies, and broaden the ontology's usability by extending its scope and applications. Although such advancements are still in the early stages of research, they represent a promising direction for the continued evolution of this ontology.

The WEEE ontology, whether as part of a DSS or as a standalone tool, holds immense potential to transform how WEEE is managed and utilized. Its scalability, adaptability, and capacity to connect critical domains position it as a pivotal development in the pursuit of sustainable WEEE management and urban mining innovation.

Chapter 5

In-depth study of PCBs

The dual functionality of PCBs serving the structural support and electrical conductivity between components have resulted in PCBs being considered the cornerstone of modern electronic devices [16]. They have a sophisticated composition made up of various metals, resins, and other materials combined altogether in order to perform well such a crucial role. On the other hand, the complexity presents a significant challenge for recycling and material recovery processes. EoL handling has opted to size reduction through shredding or milling as an initial treatment step to contrast the complexity of the PCB structure and increase the efficiency of subsequent metal extraction processes leading to metal extraction processes being highly dependent on the particle size after the size reduction phase [66].

Recent research has enabled a more knowledgeable comprehension of PCB composition across different electronic devices. An examination of PCBs from computers, laptops, and televisions revealed their distinct material composition and distribution within the various particle size fractions [113]. The findings from the study indicated that metals such as copper, zinc and aluminium are predominantly found in fractions of relatively large size ranging between 0.18 and 0.25mm, meanwhile precious metals and rare earth elements accumulate in finer particle sizes. These results align with the results from complementary research which investigated the metal content in PCBs from computers, laptops, mobile phones, and televisions along with evaluating the various digestion methods for accurate sample preparation and analysis [41]. The study resulted in defining acid treatments using hydrogen fluoride (HF) as specified in the USEPA 3052 method as the most effective in dissolving metals regardless of their entrapment within the characteristic silica matrices of PCBs.

Despite the current studies revealing valuable insights, there persists a significant knowledge gap regarding the variation of material composition of PCBs internally within a harmonised category of WEEE, for instance computers. This gap has implications for treatment optimization hindering the informed decision about the necessity of PCB separation during treatment processes and the yielded benefits from such separation due to our lack of understanding of the extent of material variation among the different PCB types. Bridging this gap supports the creation of a knowledge base for precise material content of PCBs which in turn enhances the accuracy of modelling efforts and improves prediction capabilities in designing recycling processes. This knowledge would be valuable in supporting the decision-making for the WEEE handling dilemma. Thus, optimising sorting and separation strategies, developing targeted recovery processes, enhancing the precision of material flow analyses, improving economic assessments of recycling operations.

This chapter aims to contribute to the enrichment of the knowledge surrounding PCBs particularly extracted from computers as a step forward towards the aforementioned benefits within the WEEE handling sector. The investigation discussed hereafter revolves around the material variation of different PCB types and models in addition to the evaluation of an improved pre-treatment technique using the DMSO organic solvent. This chapter aims also to leverage one of the challenges faced during the design and building of the DSS and the ontology previously discussed in Chapter 4 being the lack of precise data and the predominance of generic data for material content in WEEE.

5.1. Characteristic analysis of PCBs

In this part of the study, the focus is on the investigation of the material content of PCBs of different types and the evaluation of the variation in material content among both the different types of PCBs and the different models of the same type in an attempt to define trends and address the necessity of type and model-based separation of PCBs.

For this purpose, PCBs sourced from personal computers were analysed. They are PCBs from retired computers from the Politecnico di Torino, Italy which are collected and tested by the student team WEEE[1]. The PCBs in discussion are of three different types; namely: Motherboards, Random Access Memory (RAM), and Central Processing Units (CPUs) and chipsets. To be able to objectively analyse the different types and draw conclusions regarding trends in material content 9 motherboards, 10 RAM and 11 CPUs and chipsets were analysed individually.

The preparation process of the samples started by manually desoldering and removing the mounted components on the PCBs using indirect heating of the PCBs which would melt the solder used to attach the mounted components and facilitate their disassembly. At the end of this step, a stripped PCB substrate made of a composite structure of glass fibres, metals and resin is obtained. Next, the RAM, and CPU and chipset modules were manually cut using a Guillotine paper cutter reducing them to slivers of 1 cm wide. Further processing to transform them into fine homogeneous particles ready for sampling was reached after the use of an M20 IKA Werke universal mill operating at a fixed speed of 20,000 rpm for 14 minutes.

Given the larger size of motherboards, the initial size reduction phase was achieved using a Tiger Shark S100 Counter-rotating Blade Mill (Fulltech Mills) instead of the manual cutting using the Guillotine paper cutter. This reduction phase produced small particles of under 5.6 mm which allowed to further pulverize the motherboards using the same M20 IKA Werke universal mill, operating under identical conditions as those used for the CPU and RAM modules. The resulting fine powder was for sampling and subsequent analyses.

A quantitative analysis of the prepared samples was conducted using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), Inductively Coupled Plasma Mass

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[1] The WEEE team is responsible for collecting WEEE from across the university, testing for functioning components and refurbishing or reusing functional parts

Spectrometry (ICP-MS), and X-ray Fluorescence Spectroscopy (XRF) for which auxiliary refinement of the samples was carried out in order to certify the reliability and accuracy of the results. The refinement process began with calcinating the samples overnight at 500°C in a muffle furnace (Carbolite Gero). This step targeted the removal of the organic materials present in the sample which would otherwise influence the precision of the results obtained from the different analysis methods. To render the samples more homogeneous, they were then grounded into finer powder using a vibratory mill (Herzog) equipped with a tungsten carbide disc mill. At this point, the samples were ready for the different quantitative analysis methods.

For the XRF analysis, at least 2g of the prepared powder was placed in a cell with a surface of 30mm in PPE plastic making it ready to be analysed using an Axion XRF spectrometer (Panalytical). Regarding the ICP-OES analysis, between 0.05g and 0.1g of the prepared powder was put in a digestion vessel. The sample is then treated with 3 mL of 40% hydrogen fluoride (HF) and heated on a plate until complete evaporation at 180°C followed by another HF treatment at the same conditions of 180°C using the same quantity of 3 mL to ensure complete digestion. Once the sample cooled, 8 mL of aqua regia (3:1 HCl/HNO3) was added, and the mixture was digested in a microwave digester (ETHOS ONE, Milestone). For this step, the digestion procedure included a temperature ramp heating the sample to 200°C over 10 minutes, followed by maintaining isothermal conditions at 200°C for 5 minutes, then heating to 230°C over 5 minutes, before finally maintaining isothermal conditions at 230°C for 10 another minutes. After the digestion, the sample was diluted to 50 mL using deionized water before analysis.

5.1.1. Comparison among different models of the same PCB type

The first part of the quantitative analysis examines the material content of each of the sampled PCBs separately and compares the results among the same PCB group. This aims to identify trends among PCBs of the same type and evaluate the impact a model-based separation would have based on the variance in material content from one model to another.

5.1.1.1. Personal Computer motherboards

Before the preparation of the samples and after the stripped motherboards were obtained, their respective weights were recorded; this data was then used in the analysis and as a reference for correlations. In addition, other useful data was collected such as the manufacturing dates of the motherboards studied and their estimate current price; mainly the sampled motherboards had a manufacturing year between 2005 and 2011[2].

All the collected data was then analysed with the aim to figure out potential trends. Starting with a careful inspection of the weights recorded and comparing them to the year of

[2] Current market prices for these motherboards were obtained from online marketplaces, primarily eBay

manufacture which reveals a general trend of decreasing weight. This is likely driven by industry efforts to produce lighter and more portable products. Opposing the decrease in weight is the current market price which shows a low correlation coefficient of -0.28 suggesting the absence of relationship between the motherboard weight and the current market value. The year of production, weight and current market value of each of the analysed motherboards are visualized in Figure 13. The prices are expressed in Euros and the weights in grams.

Among the 9 analysed motherboards, weights of the stripped motherboards ranged from a minimum of 109g to a maximum of 257.5g with the average being 179.5g. This weight of a stripped motherboard represents on average 39.92% of the total weight of a motherboard with all components mounted. Not to be overlooked is the organic component which constitutes an astounding portion of about 24.7% of the weight of the stripped motherboard with a standard deviation of 3.38. This is calculated as the weight difference of the samples during the calcination process in the muffle furnace to remove the organic materials. With such a high presence in the motherboard PCB, the organic component remains of a significant potential for recovery and reuse in alignment with the green economy principles.

Figure 13. Visualization of the sampled motherboard PCB weights in grams and their current market value in Euros. Shown between brackets next to the name of each sample is the year of production

A thorough study of the obtained data discloses the industry's efforts to minimize the environmental and health risks associated with flame retardants, a chemical commonly used in the manufacturing of PCBs and usually contains bromine [39], [40]. This conclusion can be reached based on the reduction in bromine content in motherboard PCBs over the years. A similar decreasing trajectory is exhibited by the copper content; however, in this case it can be associated to the material optimization strategies followed by manufacturers in an attempt to bring down the production costs. The content of copper within motherboard PCBs suggests a moderately strong correlation with the motherboard's current market value with a calculated coefficient of 0.359 hinting the potential role copper content has in determining the economic value of motherboards in the context of material recovery and recycling. A representation of the relationship between copper content and the current market price of the motherboard PCBs is shown in Figure 14.

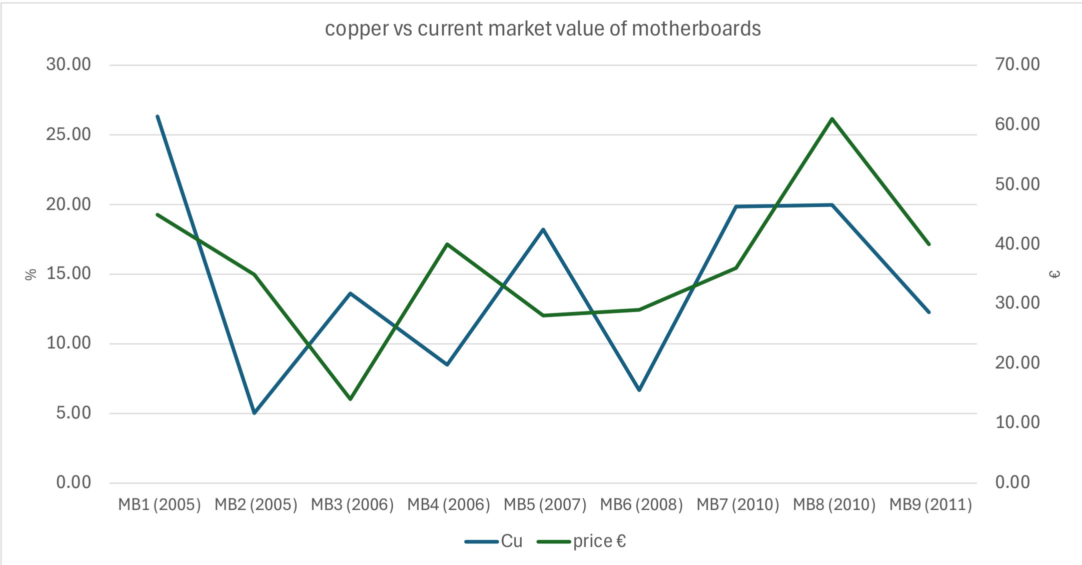


Figure 14. The correlation between the percentage of copper contained within the motherboard PCBs and their respective current price expressed in Euros

Silver is among the precious materials sought after in PCBs. Observing the data from the material characterisation of motherboard PCBs leads to noticing the consistent increase in the amount of silver used in motherboards between 2005 and 2010; an increase that is interrupted in 2011. The decline can be referred to the notable spike in the global silver price during the year 2011 that broke the steady increasing curve in silver prices from before 2005 to 2010 [123], [124]. The sharp rise in market price might have driven manufacturers to reduce silver usage in motherboard PCBs to maintain the production costs. The hypothesis is rendered more solid after the careful inspection of the current market value of the motherboards and the correlation with their silver content, as depicted in Figure 15. Between 2007 and 2011 the correlation is evident with a coefficient of 0.462- being one of the highest correlations identified between a material content in motherboard PCBs and their current market price. However, the correlation decreases significantly when considering the entire study period from 2005 and 2011 to 0.185; a decrease which reflects the influence of external market factors over the longer timeframe.

On the mentioning of strong correlations between material content and current market price, the content of titanium has a strong negative correlation of -0.829 indicating that the higher the titanium in the motherboard PCB the lower the market value is. Tungsten and tin follow respectively with a positive correlation to the market value of 0.59 and 0.585 suggesting their positive contribution to the economic value of the motherboards.

Another interesting link is the potential impact some materials have on the weight of motherboard PCBs. Analysing the relation between motherboard weights and their content of tungsten, tin, and copper exhibits strong correlations. These materials demonstrate inverse relationships with the weight of motherboard PCBs, where higher content of these materials corresponds to lighter motherboards. Tungsten had the strongest correlation with a coefficient of -0.7 and copper the lowest at -0.525. This trend suggests that material optimization strategies may have been employed by manufacturers to achieve more compact and efficient designs.

These findings confirm the importance of understanding material trends in PCBs as a way to optimize the recovery strategies and support sustainability in the WEEE management sector.

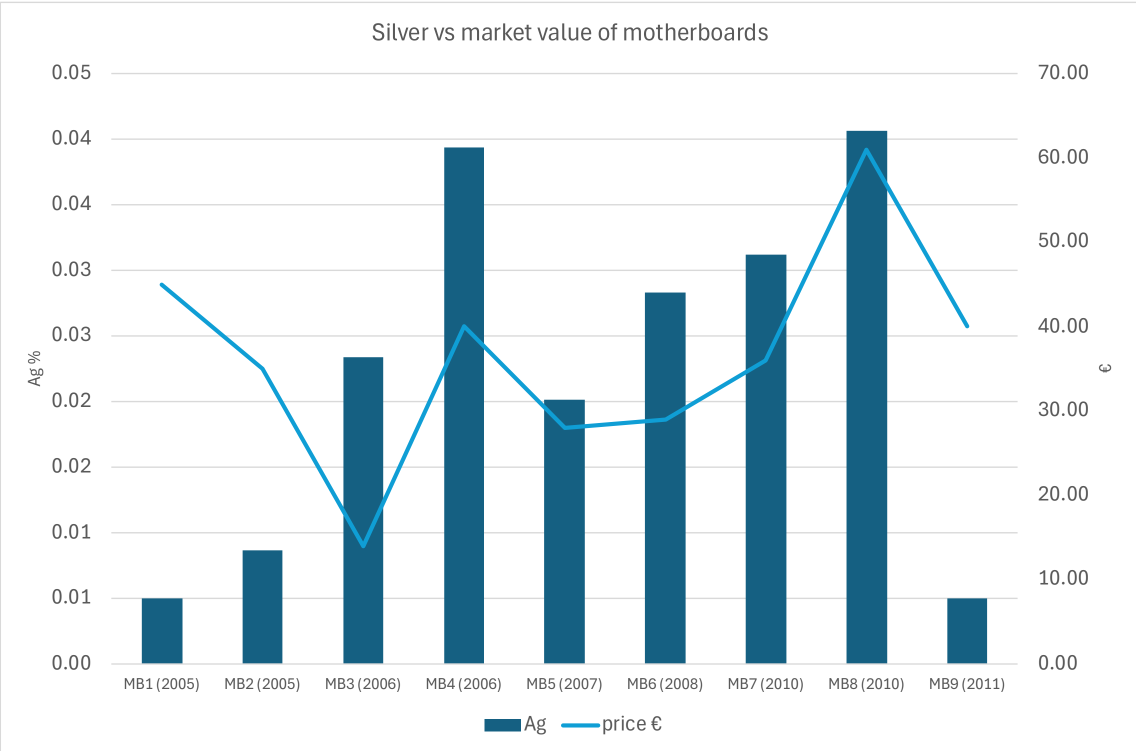


Figure 15. The potential impact of silver content % in motherboard PCBs on their respective current market value shown in Euros

Besides the insights obtained from the analysis of the nine motherboard PCBs regarding relationships between materials contents, weights, and trends over time, the analysis provides an imperative standpoint on the material content and its variation among different models of the same type PCBs, in this case motherboard PCBs. The analysis shows that both copper and silicon are the most abundant materials present in motherboard PCBs. Copper is found at an average concentration of 14.5% with a standard deviation of 6.7 followed closely by silicon which averages 13% with a standard deviation of 5.2. The maximum detected copper and silicon content among the analysed samples is found in motherboard MB1 (shown in Figure 16) at 26.35% and 15.22% respectively. On the other end of the spectrum, MB6 (shown in Figure 16) has the lowest detected content with copper and silicon significantly reduced to 6.68% and 6.83% respectively. Despite the variations, sometimes substantial, in the overall inorganic material content across samples, there is a consistent trend where copper and silicon dominate the composition occupying the top positions interchangeably followed by calcium, aluminium, and tin as shown in Figure 16. Two important observations cannot be overlooked, first the consistency in the material content of copper and silicon which underscores the critical role of these materials in motherboard construction regardless of variations in total material content. Second is the variation observed in secondary materials such as that of lead with relatively higher presence in samples MB1 and MB2, barium having a notable presence in MB9, and MB7 being rich in zinc. However, such alteration in secondary materials have little to no impact on the overall ranking of the most prevalent materials. The representation in Figure 16 of the material content is meant to be intuitive where the size of each block representing a material, both thickness and length, indicates the relative abundance of the material within the sample.

The complete results obtained from the XRF analysis across the nine motherboard PCBs are shown in Table 6, where the concentrations of 22 different detected materials as a percentage of the total original sample weight are reported. For easier understanding of the data, cells highlighting significant relative content are shaded in varying intensities of green, with darker shades indicating higher concentrations. For instance, copper in sample MB1 is highlighted as the darkest shade, reflecting its status as the most abundant material, comprising 26.3% of the sample's total weight—the highest among all materials and samples analysed as previously discussed and shown in Figure 16. Moreover, the data obtained shows the extremely limited amounts of precious metals such as silver present in all of the analysed samples. Learning these trends and detailed compositions of different models of motherboard PCBs should help support informed recycling strategies.

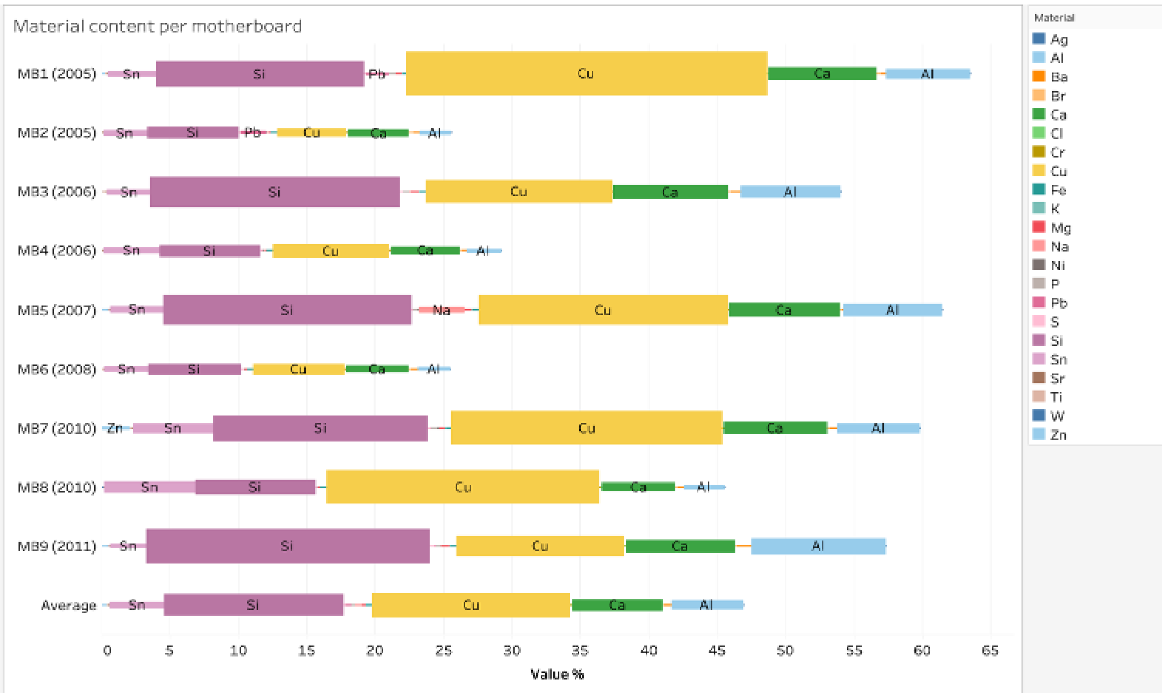


Figure 16. Visual representation of the material composition of the 9 analysed motherboard PCBs. Indicated between brackets are the years of production each sample motherboard. The size of the bars corresponds to the level of abundance of material within the sample

Table 6. The complete results of the XRF analysis of the 9 motherboard PCBs discussed

Material %	MB1 (2005)	MB2 (2005)	MB3 (2006)	MB4 (2006)	MB5 (2007)	MB6 (2008)	MB7 (2010)	MB8 (2010)	MB9 (2011)	Average	standard deviation
Ag	0.01	0.01	0.02	0.04	0.02	0.03	0.03	0.04	0.01	0.02	0.01
Al	6.16	2.31	7.34	2.51	7.21	2.36	6.05	2.92	9.80	5.18	2.59
Ba	0.43	0.47	0.77	0.38	0.16	0.50	0.58	0.46	1.04	0.53	0.24
Br	0.25	0.28	0.14	0.12	0.11	0.15	0.16	0.19	0.16	0.17	0.05
Ca	7.94	4.49	8.39	5.02	8.12	4.59	7.54	5.41	7.99	6.61	1.58
Cl	0.02	0.01	0.04	0.01	0.03	0.01	0.04	0.02	0.05	0.03	0.01
Cr	0.04	0.12	0.07	0.10	0.06	0.10	0.06	0.09	0.07	0.08	0.02
Cu	26.35	5.04	13.62	8.52	18.23	6.68	19.87	19.99	12.24	14.51	6.71
Fe	0.27	0.52	0.44	0.44	0.40	0.43	0.40	0.42	0.44	0.42	0.06
K	0.06	0.03	0.03	0.03	0.08	0.02	0.05	0.03	0.12	0.05	0.03
Mg	0.46	0.07	0.65	0.07	0.52	0.15	0.38	0.11	0.55	0.33	0.22
Na	0.01	0.09	0.01	0.14	3.38	0.06	0.01	0.00	0.01	0.41	1.05
Ni	0.01	0.05	0.02	0.04	0.02	0.04	0.10	0.04	0.04	0.04	0.02
P	0.48	0.01	0.44	0.01	0.41	0.00	0.46	0.01	0.37	0.24	0.21
Pb	1.70	1.89	0.01	0.10	0.01	0.00	0.08	0.00	0.06	0.43	0.73
S	0.11	0.13	0.27	0.11	0.05	0.17	0.22	0.13	0.37	0.17	0.09
Si	15.22	6.72	18.27	7.35	18.16	6.83	15.65	8.79	20.69	13.08	5.30
Sn	3.49	3.17	3.18	4.13	3.86	3.24	5.89	6.66	2.62	4.03	1.28
Sr	0.09	0.05	0.07	0.03	0.06	0.04	0.05	0.05	0.06	0.06	0.02
Ti	0.10	0.08	0.21	0.05	0.11	0.11	0.16	0.01	0.11	0.11	0.06

W	0.01	0.00	0.02	0.00	0.03	0.00	0.01	0.12	0.03	0.02	0.04
Zn	0.28	0.01	0.07	0.03	0.46	0.02	2.06	0.03	0.47	0.38	0.62
weight (gm)	191.70	218.77	176.40	257.51	170.70	175.57	143.13	109.27	173.60	179.63	39.68
year	2005	2005	2006	2006	2007	2008	2010	2010	2011		
Price (€)	45.00	35.00	14.00	40.00	28.00	29.00	36.00	61.00	40.00		

5.1.1.2. RAM

Applying the same systematic analysis on the ten RAM PCBs reveals information comparable to that obtained from the motherboard PCB analysis allowing a comprehensive comparison between the two types of PCBs as well as a better understanding of RAM PCBs. One of the key observations is the organic component of RAM PCBs; at an average of 25.22% of the total RAM PCB weight and a standard deviation of 3.76, the content remains consistent with that previously calculated for motherboards. Tracing back the years of production of the analysed RAMs, they were produced between 2001 and 2011. Despite the 10-year span, the weights of the analysed RAM units remain largely stable at 12.36 g and a standard deviation of 0.676 g. This is opposite to what was observed in the analysed motherboard samples which underwent noticeable weight reductions in the 6 years period analysed in this study.

Another similarity with the motherboard PCBs is the material composition of RAMs. Both types of PCBs are dominated by copper and silicon followed by calcium and aluminium. Unlike in motherboards, tin is less prevalent in RAMs with an average presence of 0.57% compared to 4.03% in motherboards. More in-depth insights regarding the individual material composition of each of the analysed RAM PCBs is illustrated in Figure 17, as previously done with motherboards, the higher material presence in a sample corresponds to a larger bar size.

Precious metals were also examined for RAM PCBs where a strong correlation between silver and gold content and the current market value of the RAM was detected. Gold, which is more detectable in RAMs than in motherboards at average of 0.02% of the RAM's weight, exhibits a strong direct correlation to current market price with a coefficient of 0.89 followed by silver at 0.837. The relationship between market values of the RAM and their respective gold and silver content is shown in Figure 18 further emphasizing the role these precious metals play in the PCB industry.

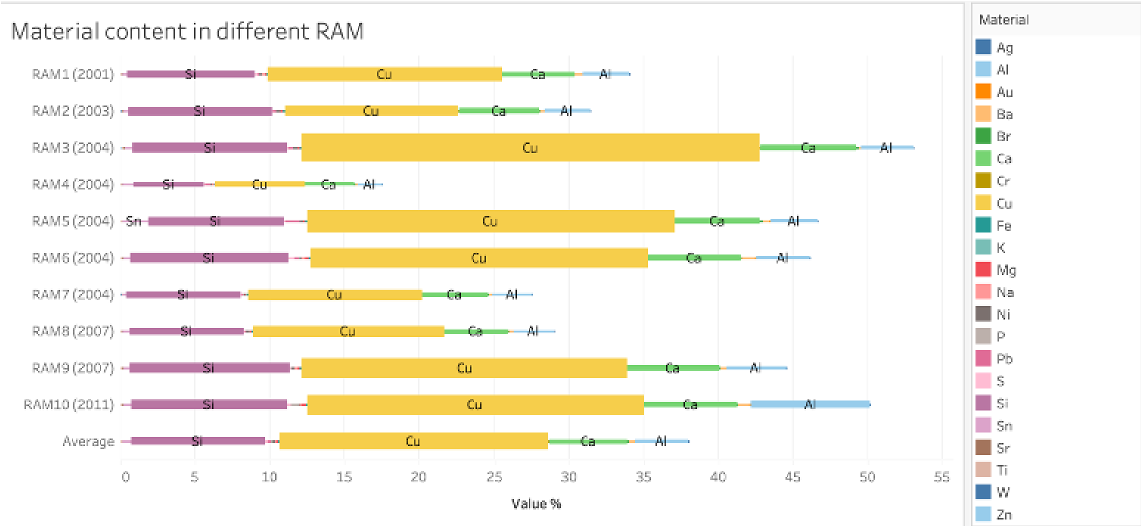


Figure 17. Visual representation of the material composition of the 10 analysed RAM PCBs. Indicated between brackets are the years of production each sample RAM. The size of the bars corresponds to the level of abundance of material within the sample

Other interesting materials found in RAM PCBs are tin, lead and bromine. These materials exhibit some of the strongest correlations with the market value of the RAM following that demonstrated by silver and gold. The calculated correlation coefficient of tin with respect to the current market price of RAMs is 0.7 meanwhile those of lead and bromine are 0.675 and 0.62 respectively. The strong correlation of tin with the market price can be seen in Figure 19 which shows both the tin content and current market price of the RAM PCBs following the same trends suggesting the significance of tin in the PCB technology. Regarding lead and bromine, the strong correlation with market price, it is suggested that such relationship is a statistical coincidence given the undesirability of both materials in the industry and the stringent regulation of their use due to their health and environmental implications [5], [6], [17], [19], [34]. With such limitation, it would be assumed that an inverse relationship with price would be present, unlike the current reality, as the lower the PCB contains of these materials the more lucrative it should become; further supporting the hypothesis that this correlation is of no significance beyond the numerical. On the mentioning of the limitations applied to the use of lead and bromine, the average of content of lead in the RAM PCBs is 0.24% seemingly exceeding the threshold limit set by the RoHS at 0.1%. A final observation regarding the bromine and lead content is the strong correlation between the presence of both materials in the RAM PCBs with a correlation coefficient of 0.878.

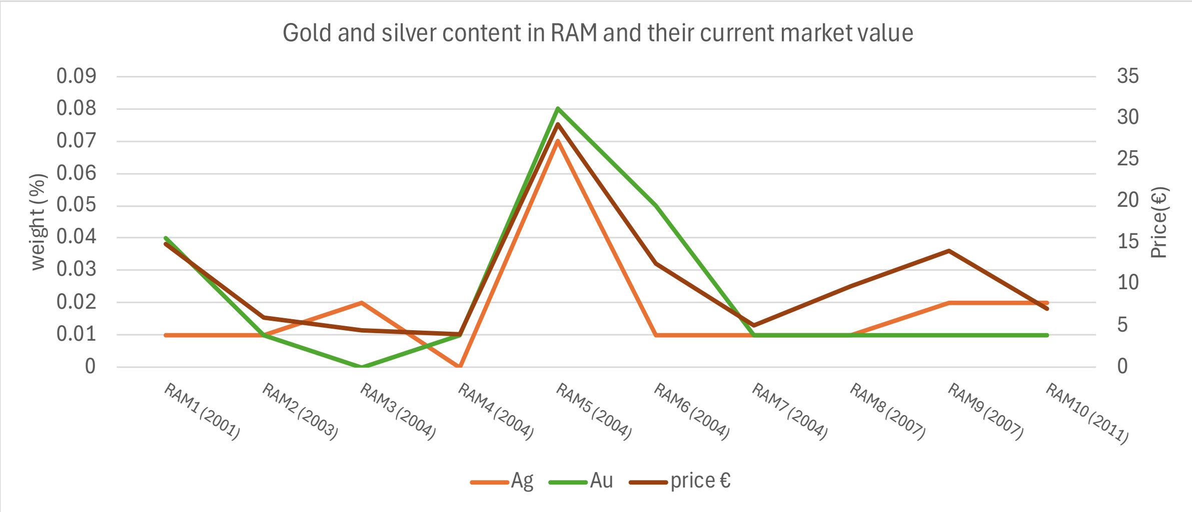


Figure 18. The impact gold and silver content has on the current market price in Euros of the analysed RAMs

Although the material composition of RAM PCBs is somewhat similar to that of motherboards where silicon, copper, calcium, and aluminium are dominant materials the closer examination of the data shows a significant variability in the material content percentage across the sample pool; fluctuation strongly present even between RAM PCBs which share the same year of production. This lack of consistency is evident in the relatively large standard deviation such as that calculated for copper standing at an astounding 7.1 despite an average content of 17.98%. Such fluctuation is likely influenced by the differences in manufacturing practices and design requirements given the complex tasks carried out by the RAM which require speed and efficiency. To further understand the scale of variability, the material content is plotted both on log scale shown in Figure 20 (a) and as content percentage shown in Figure 20 (b). In both representations the complete absence of a steady pattern over time can be well observed; this in term complicates the task of dealing with RAMs generically as significant variances are present. Additionally, the four most dominant materials- copper, silicon, calcium, and aluminium- are presented in Figure 21, which shows the trend of their content among the different sample pool.

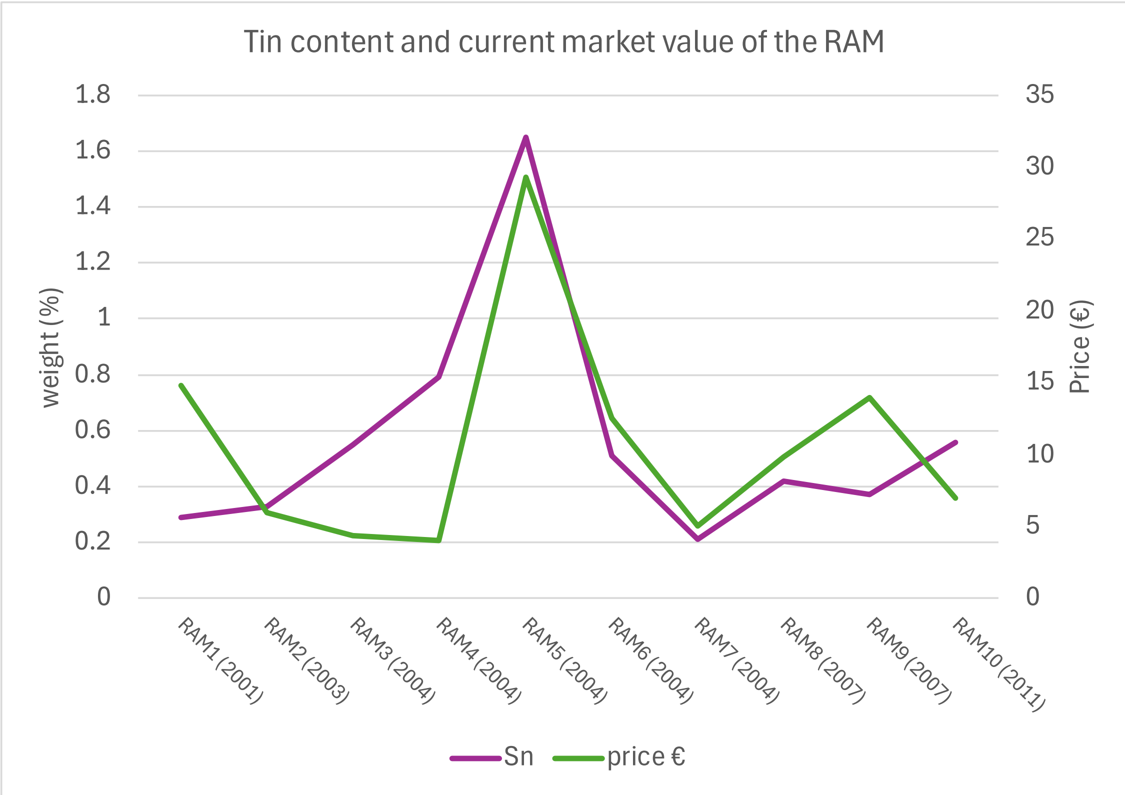
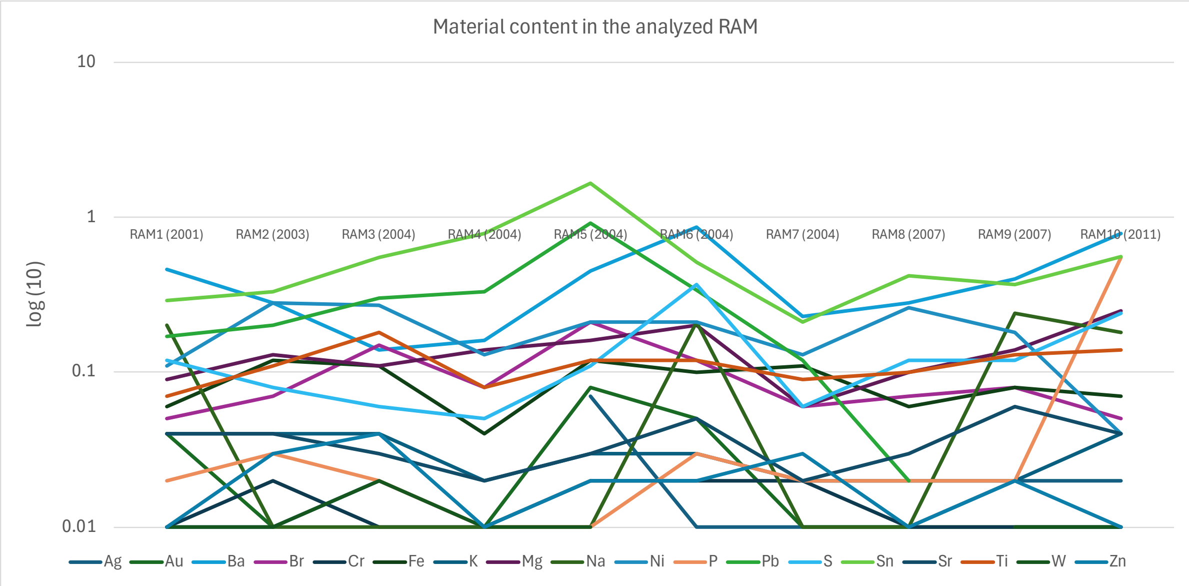
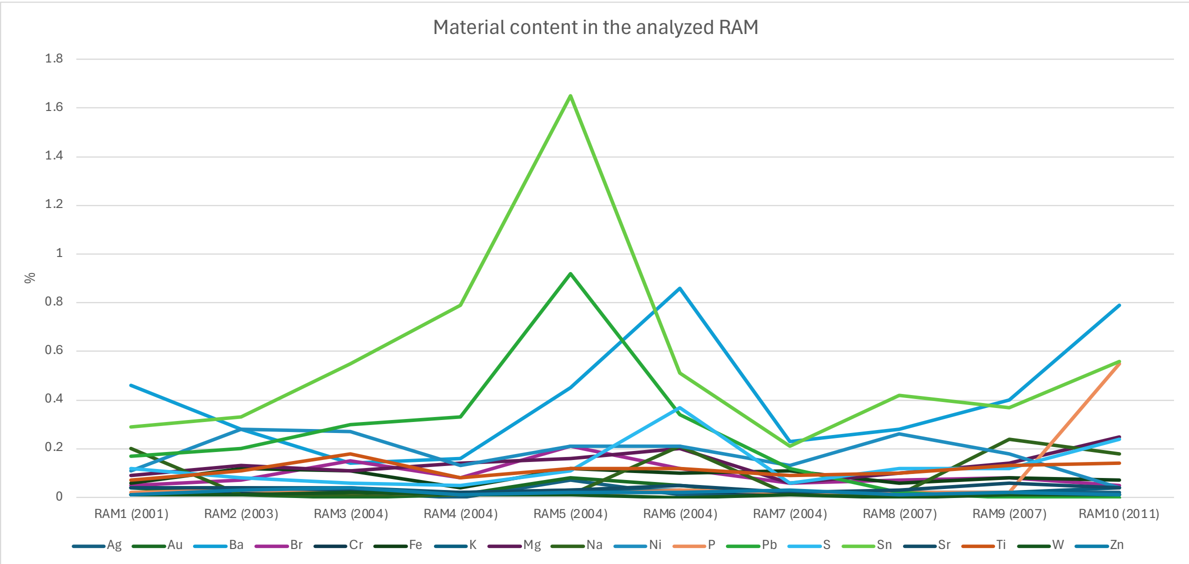


Figure 19. A demonstration of the strong correlation between the market price in Euros of the analysed RAMs and their tin content



(a)



(b)

Figure 20. The absence of trends in material content of the analysed RAM PCBs further complicating their handling. In figure (a) the material content is shown on a log scale while in (b) the graph represents the content percentage of each material

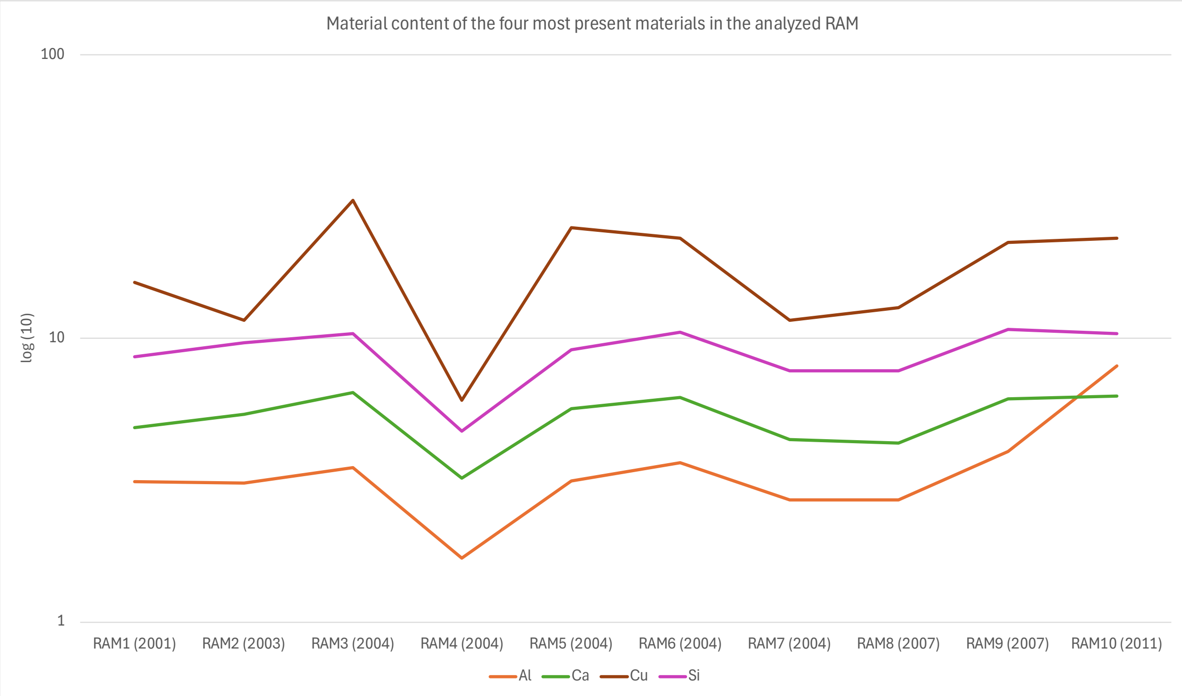


Figure 21. A log scale representation of the content percentage of the four dominantly present materials found in the analysed RAM PCBs.

Just as with motherboards, the 22 detected materials during the XRF analysis of the ten RAM PCBs are listed in Table 7. The table also includes some details about each RAM sample such as the year of production, the weight, and the current market price; all of which are data used in the analysis and in exploring potential trends. The highlighted cells in different shades of green correspond to the significance of material contribution where cells representing materials with higher concentrations are shaded in darker green indicating greater relative content of the material in all of the samples such as seen in the case of copper in sample RAM3.

The results discussed show the complexity of RAM PCBs material composition with comparison to their motherboard counterparts complicating the standardizing of recovery strategies and emphasizing the importance of detailed compositional analysis of among different types and models of PCBs to offer an optimised and tailored WEEE management policy.

Table 7. The complete results of the XRF analysis of the 10 RAM PCBs discussed

Material %	RAM1 (2001)	RAM2 (2003)	RAM3 (2004)	RAM4 (2004)	RAM5 (2004)	RAM6 (2004)	RAM7 (2004)	RAM8 (2007)	RAM9 (2007)	RAM10 (2011)	Average	Standard deviation
Ag	0.01	0.01	0.02	0	0.07	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Al	3.13	3.08	3.51	1.68	3.14	3.64	2.69	2.69	3.99	8.01	3.56	1.60
Au	0.04	0.01	0	0.01	0.08	0.05	0.01	0.01	0.01	0.01	0.02	0.02

Ba	0.46	0.28	0.14	0.16	0.45	0.86	0.23	0.28	0.4	0.79	0.41	0.23
Br	0.05	0.07	0.15	0.08	0.21	0.12	0.06	0.07	0.08	0.05	0.09	0.05
Ca	4.83	5.39	6.45	3.22	5.66	6.17	4.39	4.28	6.12	6.26	5.28	1.01
Cr	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Cu	15.69	11.58	30.69	6.03	24.56	22.58	11.59	12.8	21.81	22.49	17.98	7.20
Fe	0.06	0.12	0.11	0.04	0.12	0.1	0.11	0.06	0.08	0.07	0.09	0.03
K	0.04	0.04	0.04	0.02	0.03	0.03	0.02	0.02	0.02	0.04	0.03	0.01
Mg	0.09	0.13	0.11	0.14	0.16	0.2	0.06	0.1	0.14	0.25	0.14	0.05
Na	0.2	0.01	0.01	0.01	0.01	0.21	0.01	0.01	0.24	0.18	0.09	0.10
Ni	0.11	0.28	0.27	0.13	0.21	0.21	0.13	0.26	0.18	0.04	0.18	0.07
P	0.02	0.03	0.02	0.01	0.01	0.03	0.02	0.02	0.02	0.55	0.07	0.16
Pb	0.17	0.20	0.3	0.33	0.92	0.34	0.12	0.02	0	0	0.24	0.26
S	0.12	0.08	0.06	0.05	0.11	0.37	0.06	0.12	0.12	0.24	0.13	0.09
Si	8.62	9.62	10.37	4.71	9.11	10.52	7.68	7.7	10.72	10.4	8.95	1.77
Sn	0.29	0.33	0.55	0.79	1.65	0.51	0.21	0.42	0.37	0.56	0.57	0.39
Sr	0.04	0.04	0.03	0.02	0.03	0.05	0.02	0.03	0.06	0.04	0.04	0.01
Ti	0.07	0.11	0.18	0.08	0.12	0.12	0.09	0.1	0.13	0.14	0.11	0.03
W	0.01	0.01	0.02	0.01	0.01	0	0.01	0	0.01	0.01	0.01	0.01
Zn	0.01	0.03	0.04	0.01	0.02	0.02	0.03	0.01	0.02	0.01	0.02	0.01
weight (gm)	11.92	12.63	12.12	11.71	11.93	12.93	13.18	12.19	11.35	13.62	12.36	0.68
year	2001	2003	2004	2004	2004	2004	2004	2007	2007	2011		

price (€)	14.8	6.00	4.4	4	29.3	12.5	5	9.8	14	7		

5.1.1.3. CPU and chipset

The third type of analysed PCBs are CPU and chipsets, where 11 different samples have been examined. Unlike the reported consistency in the material composition of two previously studied types, CPUs and chipsets stand out with their material composition. They have an organic content that notably fluctuates across the sample pool, ranging from as low as 5% content to a staggering 34% surpassing the organic content average in both RAM and motherboard PCBs. This variability leads to the average organic content of CPU and chipsets being 13.56% with a substantial standard deviation of 8.16. The lower organic content in some of the samples results in this type of PCBs being considered a rich source of metals given the high inorganic to organic ratio and despite their lightweight nature. The weight range of the tested CPU and chipsets is between 8.47g and 0.52g further highlighting their compact design expanding the gap between them and the other studied PCB types.

Regarding the inorganic composition of the sampled CPUs and chipsets, similarities are shared among all three studied types with a consistent domination of copper and silicon followed by aluminium and calcium. The presence of tin in significant quantities bring CPUs and chipsets closer to motherboards which have a similar composition and further away from RAM PCBs. Translated in numbers, the average copper content s 20.18%, though it demonstrates a considerable variability represented by the high standard deviation of 11.8 resulting from the maximum and minimum values being 37.12% and 2.06%. The average silicon content in the samples is 12.08% with a standard deviation of 4.7 meanwhile that of aluminium and calcium is closely comparable at an average of 2.35% and 2.99% respectively.

Once again lead levels raise a flag with their high concentrations in some samples reaching as high as 5.77% and with an average content of 1.54% throughout the sample pool. These levels exceed the permissible threshold regulated by RoHS and other legal frameworks as well as outdo the previously reported high levels of lead and bromine in RAM PCBs. In addition, it highlights the potential health and environmental risks associated with processing these specific types of PCBs and emphasizes the need to studies dissecting the composition of different PCBs to avoid underestimating the risks as a result of referring to PCB generically.

The total material composition of the CPU and chipsets studied is presented in Figure 22. From the figure, the two samples CPU5 and CPU6 which are two CPUs of the same model show inconsistency in their material composition. The discrepancy is likely due to the inhomogeneity of the samples which was a common challenge faced during the study. Despite the irregularity, the general trend in material composition remains unswerving with copper as the most prominent materials followed by silicon, calcium and aluminium.

Similar to RAM, CPU and chipsets require high performance and efficiency since they play an important role in supporting complex computational and control processes in the computer. This is reflected in their higher content of precious metals such as gold and silver where the average gold content among the samples is 0.04% and that of silver is 0.06%, approximately three times the levels of silver reported in RAM and motherboard PCBs. The variation of gold and silver content in the analysed CPU and chipsets is depicted in Figure 23. The discussed results from the XRF analysis of the 11 CPU and chipset samples are indicated in

Table 8 where the content percentage of 21 material is reported relative to the total sample weight. As previously done with the presented XRF data, the table cells are highlighted in different shades of green based on the abundancy of materials in the samples. Copper is again found at outstanding percentages, thus the dark green shades.

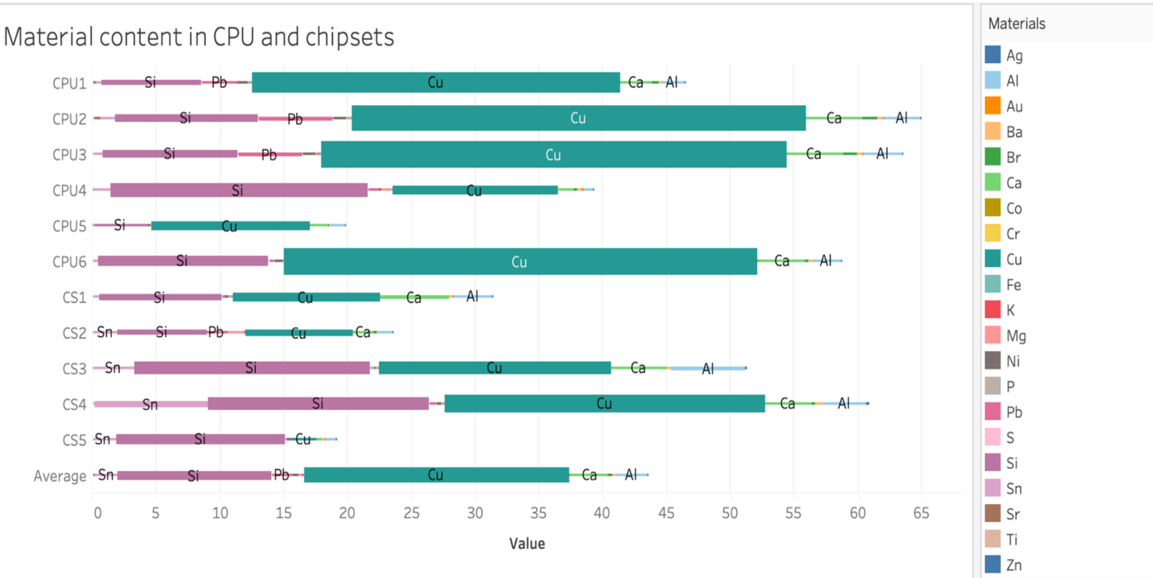


Figure 22. Visual representation of the material composition of the 11 analysed CPUs and chipsets. The size of the bars corresponds to the level of abundance of material within the sample

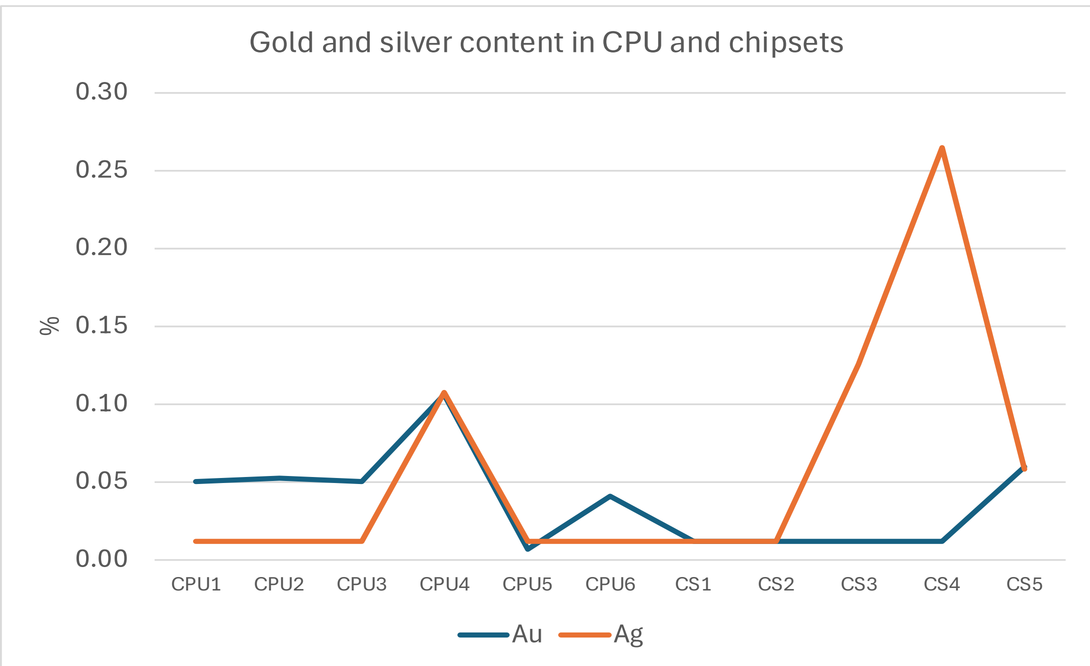


Figure 23. The percentage of gold and silver detected in the analysed CPUs and chipset samples

Table 8. The complete results of the XRF analysis of the 11 CPUs and chipsets studied

Material %	CPU 1	CPU 2	CPU 3	CPU 4	CPU 5	CPU 6	CS1	CS2	CS3	CS4	CS5	Average	Standard deviation
Cu	28.85	35.64	36.49	12.99	12.46	37.12	11.55	8.40	18.23	25.15	2.06	20.81	11.849
Si	7.84	11.23	10.57	20.11	4.11	13.32	9.60	7.02	18.47	17.30	13.29	12.08	4.786
Ca	2.46	4.42	4.37	1.23	1.41	3.69	5.38	1.56	4.35	3.63	0.37	2.99	1.572
Al	1.71	2.88	3.01	0.77	1.17	2.21	3.07	0.99	5.82	3.36	0.82	2.35	1.438
Sn	0.41	1.17	0.63	1.39	0.11	0.36	0.33	1.86	3.17	8.88	1.82	1.83	2.393
Ba	0.23	0.44	0.44	0.40	0.06	0.30	0.28	0.20	0.31	0.61	0.20	0.31	0.143
Ni	0.75	0.97	1.02	0.23	0.13	0.57	0.28	0.05	0.16	0.41	0.12	0.43	0.333
Pb	2.75	5.77	5.00	0.77	0.05	0.34	0.20	1.49	0.02	0.46	0.07	1.54	1.977
Mg	0.08	0.16	0.15	0.83	0.05	0.06	0.13	1.36	0.11	0.09	0.07	0.28	0.401
Fe	0.25	0.25	0.23	0.03	0.02	0.07	0.12	0.06	0.06	0.07	0.03	0.11	0.087
Ti	0.03	0.12	0.14	0.03	0.03	0.08	0.11	0.04	0.05	0.17	0.01	0.07	0.052
S	0.06	0.09	0.08	0.12	0.04	0.12	0.08	0.04	0.11	0.09	0.07	0.08	0.026
Br	0.57	1.17	1.12	0.22	0.07	0.28	0.06	0.28	0.01	0.31	0.02	0.37	0.396
Sr	0.22	0.42	0.01	0.01	0.01	0.01	0.04	0.01	0.03	0.01	0.01	0.07	0.124
K	0.02	0.04	0.04	0.02	0.01	0.01	0.04	0.03	0.04	0.02	0.02	0.03	0.011
Zn	0.04	0.04	0.04	0.01	0.01	0.02	0.03	0.01	0.01	0.01	0.01	0.02	0.014
P	0.05	0.05	0.05	0.01	0.04	0.06	0.03	0.05	0.21	0.06	0.02	0.06	0.049
Cr	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.003
Au	0.05	0.05	0.05	0.11	0.01	0.04	0.01	0.01	0.01	0.01	0.06	0.04	0.029

Co	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.002
Ag	0.01	0.01	0.01	0.11	0.01	0.01	0.01	0.01	0.13	0.26	0.06	0.06	0.077

5.1.2. Comparison among the different PCB types

With the valuable insights obtained from the separate analysis of different models of the same family of PCBs, gaps in our understanding of the differences present in the material composition of these different models are filled. It is now essential to focus on the average content of key materials whether for their economic and strategic value or as they are present in large quantities. This focus adds meaning to the data since it compares the material composition of the three distinct types of PCBs previously discussed.

The first outcome from the analysis of the three types of PCBs is the predominance of copper, silicon, calcium and aluminium regardless of the type of PCB. This is supported by the representation of the average material composition of each type of PCB based on the XRF analysis which is shown in Figure 24(a). The figure which represents the presence of each material with a distinct colour asserts the prevalence of these materials as well as the overall analogous composition of all three types analysed. This suggests that for the recovery of these materials all three PCBs can be treated collectively.

Understanding deeply the composition differences among the three types studied fosters the targeting of certain PCBs to maximize the extraction and recovery of specific materials as part of urban mining. All three PCBs are rich in copper which is the most abundant material found; yet the highest average concentration of copper is found in CPUs and chipsets with an average of 20.8%. The copper content then drops to 17.8% for RAMs and reaches as low as 14.5% in motherboards as shown in Figure 24(b). It is important to mention that the average weight of the motherboard PCB exceeds significantly that of CPUs and chipsets which would lead to the dependence of absolute amount of copper being extracted on the overall quantity of each type of PCB.

Silicon is the second most significant material present in all three types of PCBs. As shown in Figure 24(c), all three types of PCBs exhibit comparable amounts levels of silicon with motherboards containing the highest average amount at a 13%.

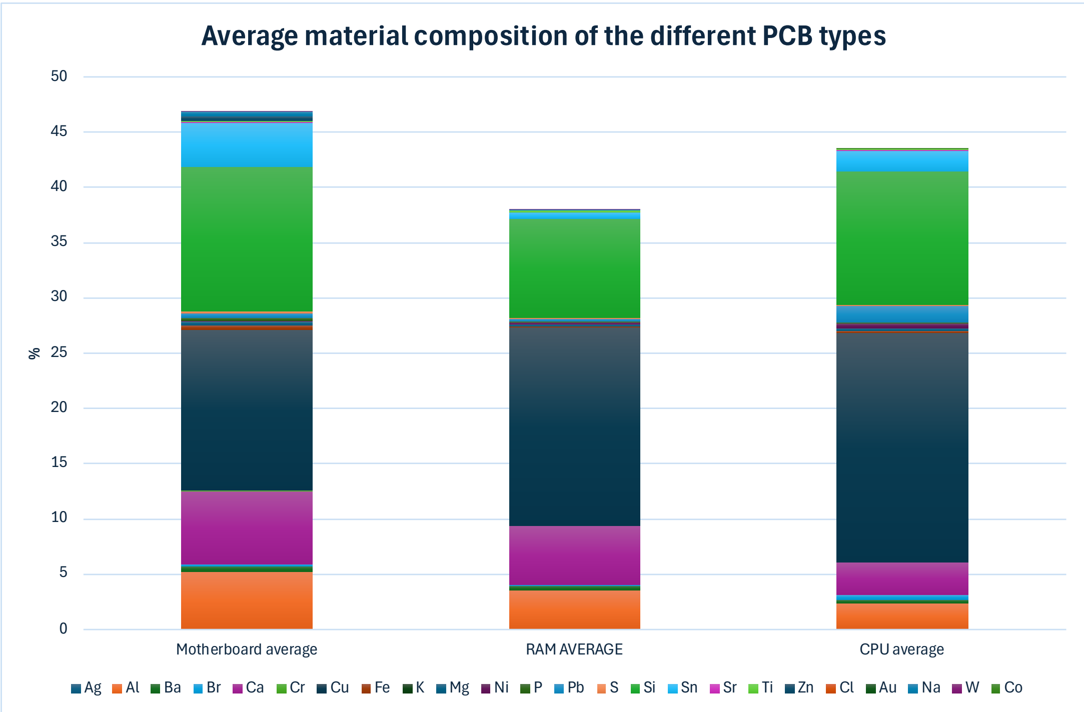
The favourability of motherboards continues as a notable source of aluminium and tin. In Figure 24(d) the average amount of aluminium for each of the three types of PCBs is shown with motherboards standing out at nearly twice the average aluminium content found in CPUs and chipsets and 1.5 times that found in RAM. Similarly, Figure 24(e) reveals the exceptional richness of motherboards with tin material at an average content almost two folds that of CPUs and chipsets and making the average amount found in RAM PCBs comparably minimal.

For economically significant materials such as gold and silver, CPUs and chipsets take the lead. They contain almost double the average amount of gold found in RAMs. The gap grows when the average amount of silver content is compared to that of motherboards and RAMs, where the former contains one-third the reported amounts of silver in CPUs and the latter contains even less as shown in Figure 24(f).

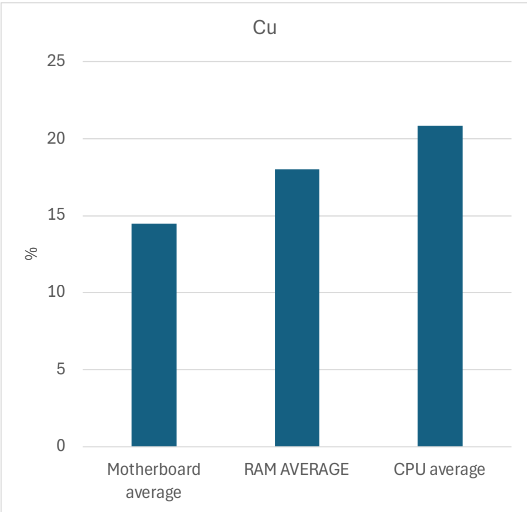
Titanium is another material worth noting given its presence on the strategic raw materials list as part of the CRM act in the EU [30]. Both RAM and motherboard PCBs contain around 0.1% of titanium as shown in Figure 24(g); however, motherboards would hold more significance despite comping second after RAMs given their typically larger weights which translates into higher absolute quantities of titanium overall.

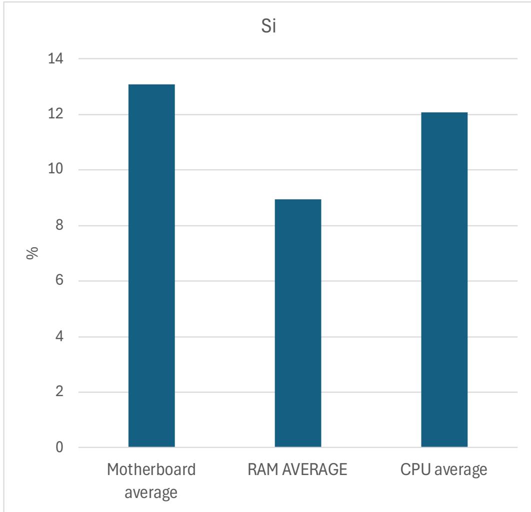
Finally, it is necessary to highlight the alarming levels of average lead content in CPUs and chipsets which are almost eight times higher than those of RAM PCBs and six times the average lead content in motherboards as shown in Figure 24(h). All three types contain elevated levels of lead exceeding the consented amount mentioned in EU regulations. As a result, it is recommended to implement additional protective measures to mitigate the adverse impact on the environment and workers involved in the WEEE handling sector.

The results obtained provide a comprehensive understanding of the PCBs both on the type and model levels as well as underscores the importance of following particularly cautious handling practices to ensure the safety and sustainability of the whole WEEE cycle.



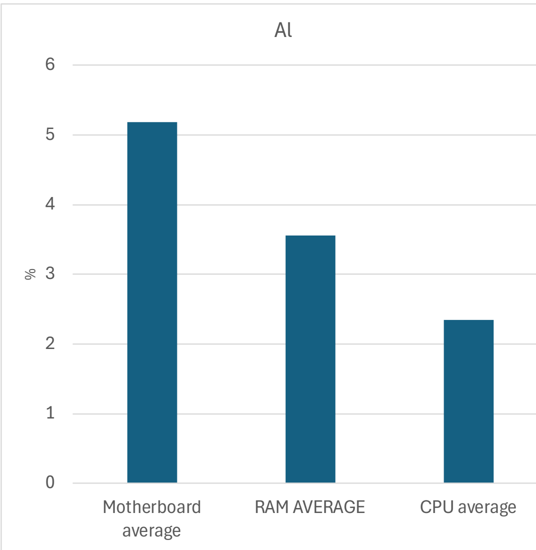
(a)

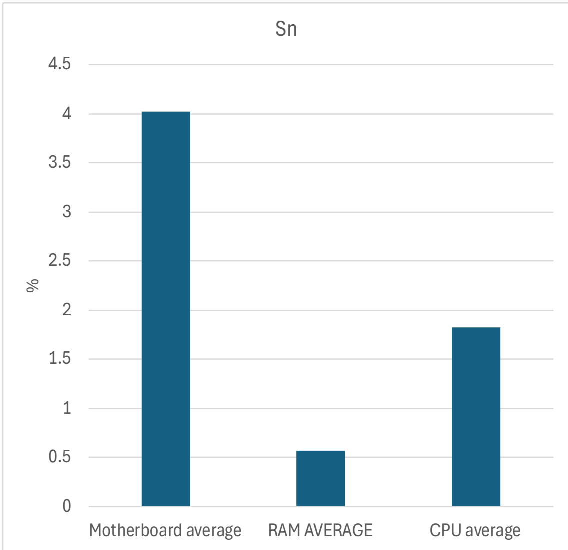

Cu
%
25
20
15
10
5
0
Motherboard average
RAM AVERAGE
CPU average


Si
%
14
12
10
8
6
4
2
0
Motherboard average
RAM AVERAGE
CPU average

(b)

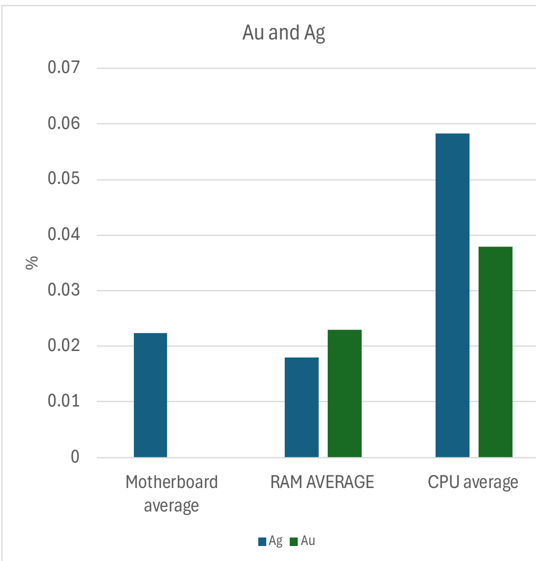
(c)

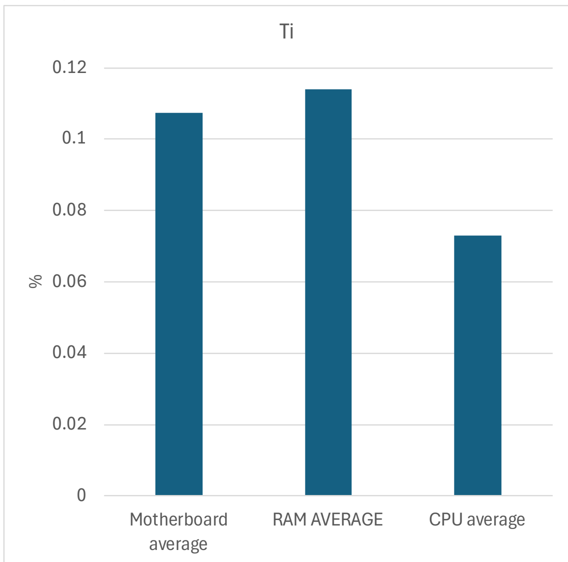

Al
%
6
5
4
3
2
1
0
Motherboard average
RAM AVERAGE
CPU average


Sn
%
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Motherboard average
RAM AVERAGE
CPU average

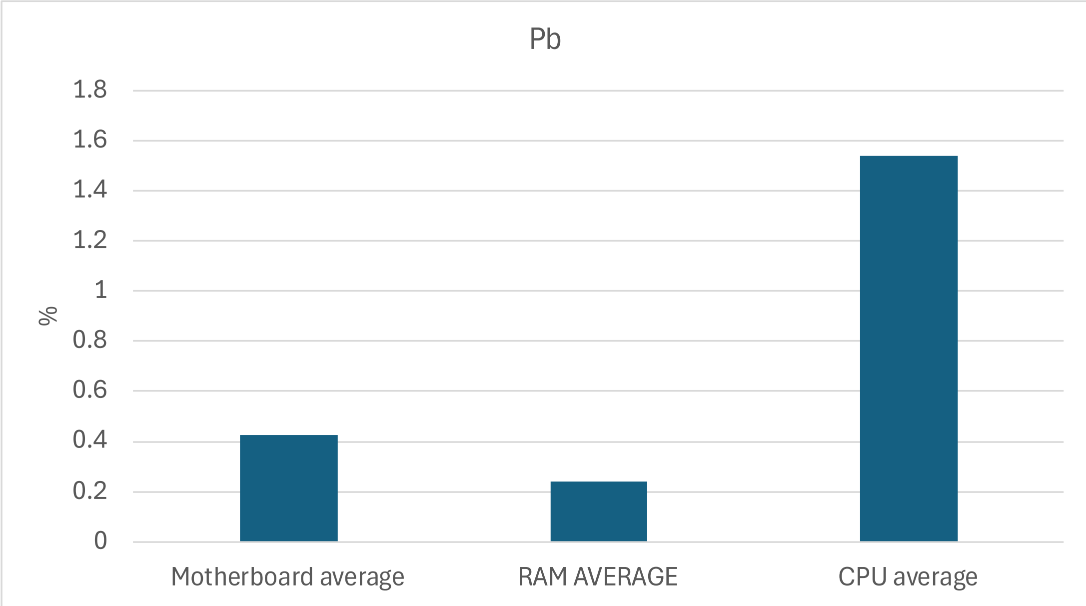
(d)

(e)


Au and Ag
%
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Motherboard average
RAM AVERAGE
CPU average
Ag
Au


Ti
%
0.12
0.1
0.08
0.06
0.04
0.02
0
Motherboard average
RAM AVERAGE
CPU average

(f) (g)



(h)

Figure 24. Representation of the average prevalent materials found in the three analysed types of PCBs (Motherboards, CPU and RAM); (a) the average material composition of three types of PCBs, (b) the average copper content among the three PCB types, (c) the average silicon content among the three PCB types, (d) the average aluminium content among the three PCB types, (e) the average tin content among the three PCB types, (f) the average silver and gold content among the three PCB types, (g) the average titanium content among the three PCB types, (h) the average lead content among the three PCB types

5.2. Study of the impact of chemical pre-treatment on the PCB hydrometallurgical treatment efficiency

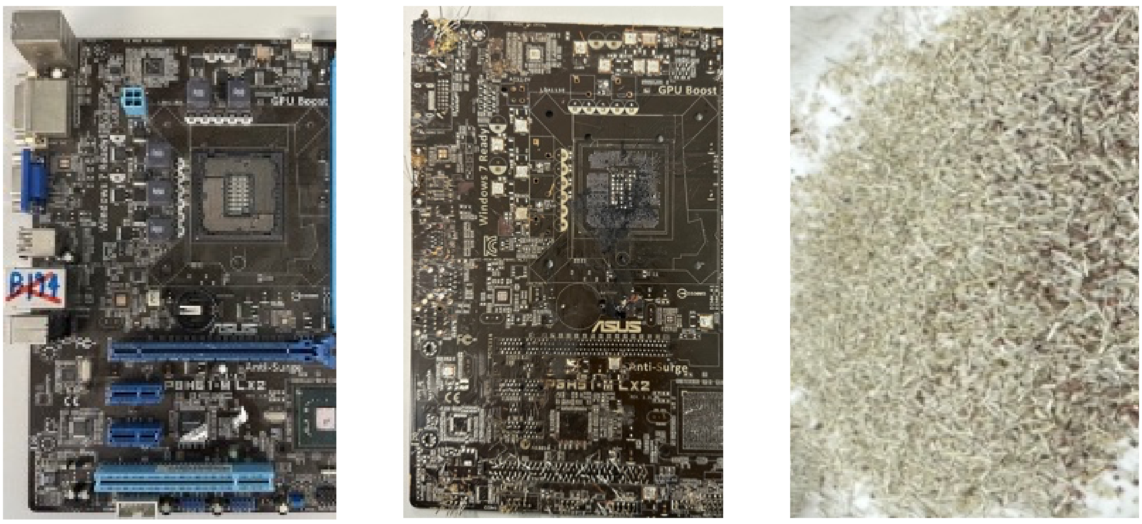
5.2.1. Materials and sample preparation

After grasping a more detailed understanding of the different types and models of PCBs, motherboards were chosen to study the impact of pre-treatment using an organic solvent such as DMSO on the copper recovery.

Again, here the motherboard PCBs are recovered from personal computers by our WEEEOpen team at Politecnico di Torino[3]. After the initial stripping phase and the removal of electronic components, the PCBs are put in a Tiger Shark S100 Counter-rotating Blade Mill (Fulltech Mills) to achieve the needed size reduction. Based on the literature [80], [81], [92], [93], studies evaluated the effect of pre-treatment using DMSO on larger sized particles. However, there remain little to no information on the impact of chemical pre-treatment on finer particles. Hence, the particle sizes chosen for this study would fall within one of three size groups. The first group (Group 1) has a particle size between 8mm and 5.6mm, his represents

[3] https://weeeopen.polito.it/

the benchmark and is the typically investigated particle size. The second group (Group 2) is the group of interest which has a particle size between 5.6mm and 2mm. This group is particularly attractive as it offers a compromise between treating the PCBs entirely or in large pieces on one hand and the extensive mechanical size reduction needed to reach the fine powder particle size with its associated hazards and potential material losses on the other hand. The final group (Group 3) is of fine particles smaller 400µm, which fits the generally recommended particle size corresponding to higher material extraction efficiency. While shredding the motherboards to reach each of these particle size groups, the motherboards shredded together to ensure a homogenous mix. At each stage the particle size is checked using sieves corresponding to the group's particle size range, thus 8mm, 5.6mm and 2mm. The sieving intermitted stages ensured the groups are homogeneous and particles fall within the suggested range. To prepare the samples for Group 3, an additional size reduction stage was introduced following the same preparation process as that done during the first part of the study to analyse the different types and models of PCBs. Once again, the M20 IKA Werke universal mill was used with its fixed speed of 20,000 rpm for 14 min to reach the fine powder stage followed by sieving quality control check with a sieve of 400µm. A sample of the motherboards used is shown in Figure 25(a) before the removal of the mounted components from the motherboard. The following phase after the stripping is shown in Figure 25(b) while in Figure 25(c) shows the final stage of Group 3 after the complete pulverization.

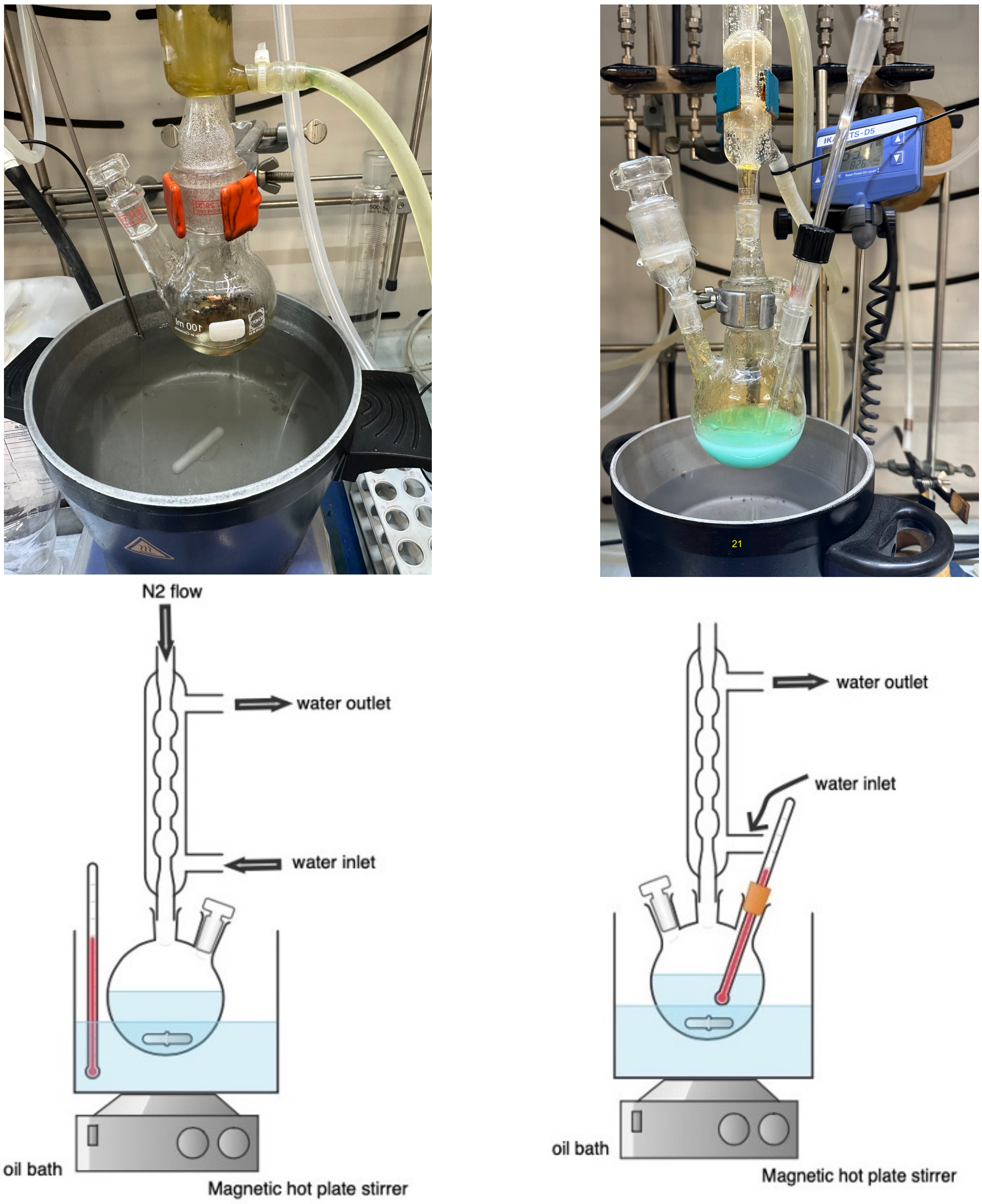


(a) (b) (c)

Figure 25. Illustrative images of the various processing stages of the retrieved motherboards during the sample preparation. (a) the motherboard PCB before any processing; (b) the stripped motherboard PCB ready for the size reduction phase; (c) the PCB powder prepared for group 3 at the final stage after the size reduction phase

After the preparation of the three sample groups, based on the extensive literature review, the conditions were chosen to be 90°C for 60 minutes, under constant N_2 flow with a DMSO ratio S/L of 1/2. These are the same conditions that were applied for the pre-treatment of particle size of range 1-1.5 cm^2 [93], and were chosen since they offer a good arrangement between the ratio S/L, time of pre-treatment and the relatively low temperature preventing the compromise of the organic material integrity at high temperatures and promoting efficiency in energy usage. The solution agitation was empirical depending on the particle size and a hot plate magnetic stirrer was used to provide both heating and stirring. The experimental setup was made up of an oil bath in which a 250 mL two neck round bottom flask was partially submerged. The top opening of the flask was fitted with an Allihn condenser consisting of a glass tube with a water jacket, formed by a series of bulbs that increase the surface area available for vapor condensation. The treatment was carried out under N2 with an open system configuration. The overall setup is shown in Figure 26 (a). After 60 minutes, the solid residue was separated by vacuum filtration and dried in a vacuum oven overnight at 35°C. Having the pretreated sample ready at hand, a portion of the obtained solid was analysed by ICP and XRF analysis and the remainder was leached.

Regarding the leaching conditions, nitric acid (HNO_3) was used with a molar concentration of 3M and a pulp density of 75g/L. The leaching processes took place for 120 minutes at 75°C [125]. Here, the experimental setup changed slightly as a 250 mL three neck round bottom flask fitted with a thermometer and Allihn condenser was used and partially submerged in the oil bath. The top opening fitted with an Allihn condenser. The complete setup is shown in Figure 26 (b). All chemicals used for both the pre-treatment process as well as the leaching process are of lab grade.



(a) (b)

Figure 26. Experimental setups for the (a) solvent pre-treatment process using DMSO setup; (b) leaching process using nitric acid setup

To set a benchmark, the three prepared sample groups were initially analysed for their material content before undergoing any type of treatment. Then each sample group were divided in two; one was used for the leaching experiment without any solvent pre-treatment and the other was first pretreated with DMSO according to the previously mentioned conditions and then taken for the leaching process. At each treatment phase, the samples were analysed to study the impact and the changes undergone. The different experimental attempts for each group are shown in the chart in Figure 27.

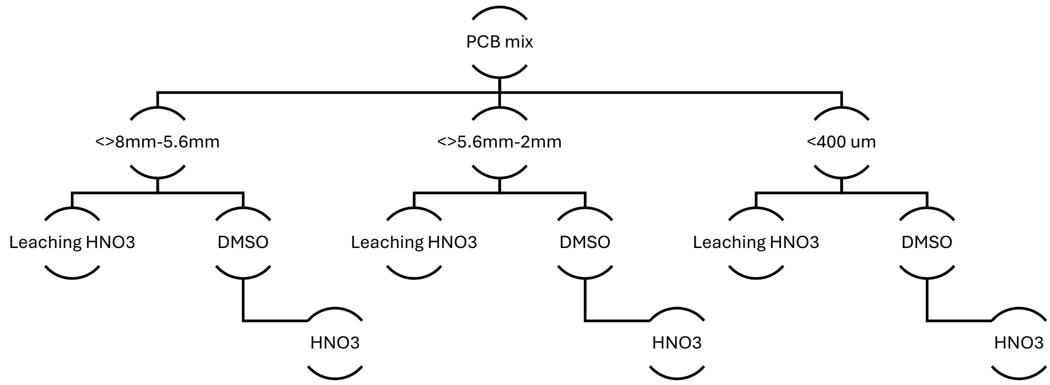


Figure 27. A chart showing the different treatment processes carried out on each sample group with different particle size ranges to study the impact of the solvent pre-treatment using DMSO on the subsequent leaching process using nitric acid

5.2.2. Impact of pre-treatment on the organic content of the PCBs

Since the organic component in PCBs is significant with a high potential of being recovered or recycled, the first part of the study inspects the impact the solvent pre-treatment has on the organic fraction of the treated PCBs. Firstly, it was important to establish the optimal stirring speeds; after multiple attempts, it was found that the best stirring speed is between 400 and 460 rpm which was suitable for all three sample groups with their different particle sizes.

After the solvent pre-treatment, the samples with the larger particle sizes belonging to Group1 and Group2 exhibited a clear swelling effect noticeable to the naked eye. This swelling and separation were less obvious in the case of the powder sample of Group3. A comparison between the before and after states of the samples from Group 2 and Group 3 is shown in Figure 28.

To confirm the extent of these structural changes, the three sample groups were analysed. However, the results show minimal change to the organic content of the samples. The change in organic content in samples of Group 1 was about 0.3% while that of Group 2 was 0.2%. For Group 3, there was no change in the organic content. This suggests that the solvent pre-treatment using DMSO does not change the material composition of the PCBs by dissolving the organic part, yet it only causes the swelling of the different layers of the substrate exposing the metals and liberating them. The hypothesis is confirmed by the previously mentioned before and after images of the samples shown in Figure 28 where the resin is seen to be present and not carried away by the solvent pre-treatment.

(a) (b)

(c) (d)

Figure 28. Images of the before and after of the solvent pretreated samples (a) Group 2 with particle size between 5.6mm and 2mm before solvent pre-treatment using DMSO, (b) Group 2 with particle size between 5.6mm and 2mm after solvent pre-treatment using DMSO, (c) Group 3 with particle size less than 400 μm before solvent pre-treatment using DMSO, (d) Group 3 with particle size less than 400 μm after solvent pre-treatment using DMSO

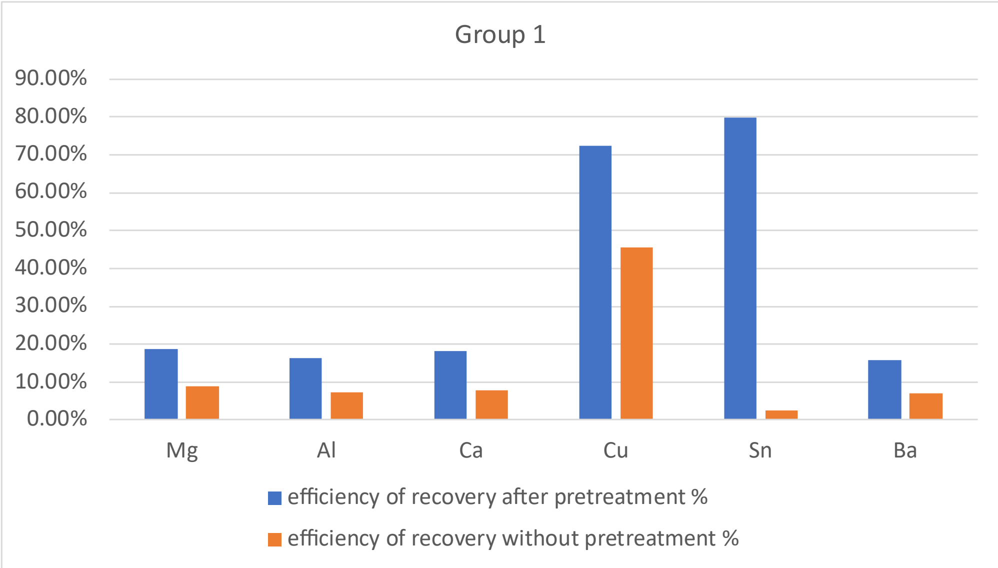
5.2.3. Impact of pre-treatment on metal recovery efficiency under different particle size conditions

The leaching part of the study produced results conforming with the evident visual change of the samples. To begin with, the empirical attempts to find the best adapted stirring speed for the leaching process which were found to be between 400 and 510 rpm.

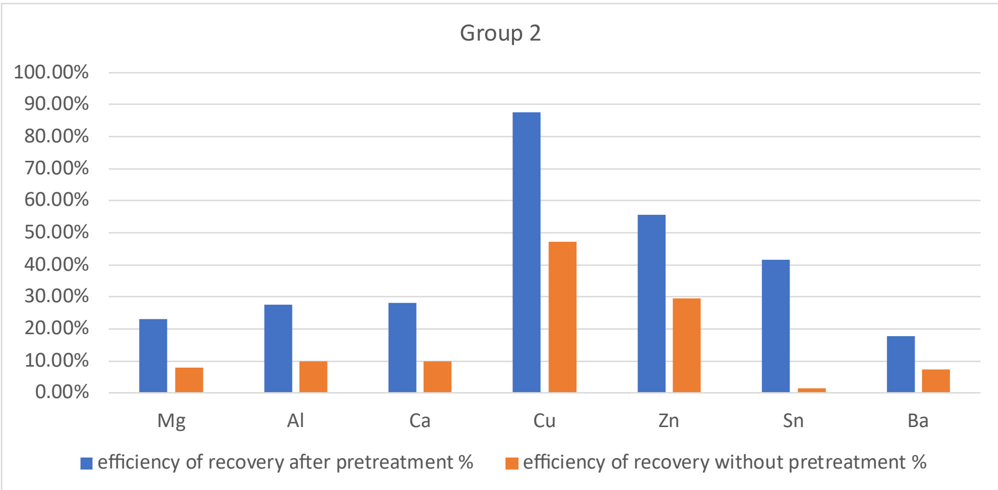
The XRF analysis of the samples under investigation showed a favourable enhancement in the metal recovery for the pretreated samples. Particularly, Group 1 had a copper recovery efficiency of 72.4% after DMSO pre-treatment, while copper recovery was only 45.5% for Group 1 samples without the pre-treatment phase. Significant improvements continue as the sample particle size decreases; for Group 2 with particle size between 5.6mm and 2 mm, the copper recovery efficiency increased from 47.3% for non-pretreated samples to 87.65% for samples treated with DMSO before leaching. Regarding the Group 3 samples which are in powder form with particle size less than 400μm, the leaching already had high copper recovery without the pre-treatment phase reaching 93.24%. However, the pre-treatment stage allowed the efficiency to reach 100%.

These results reconfirm the significant role solvent pre-treatment using DMSO has on the liberation of materials in the PCB and the enhancement of the rate of their subsequent recovery as mentioned in the literature. The results also emphasize the pivotal impact of the particle size on the pre-treatment phase which can be seen in a roughly 30% improvement in the copper recovery efficiency for larger particle sizes (Group 1 and Group 2) while the impact becomes less attractive in the case of the fine particles of Group 3. Since the finer the particles are the materials are more liberated rendering the solvent pre-treatment phase unnecessary especially with the added cost of resource usage.

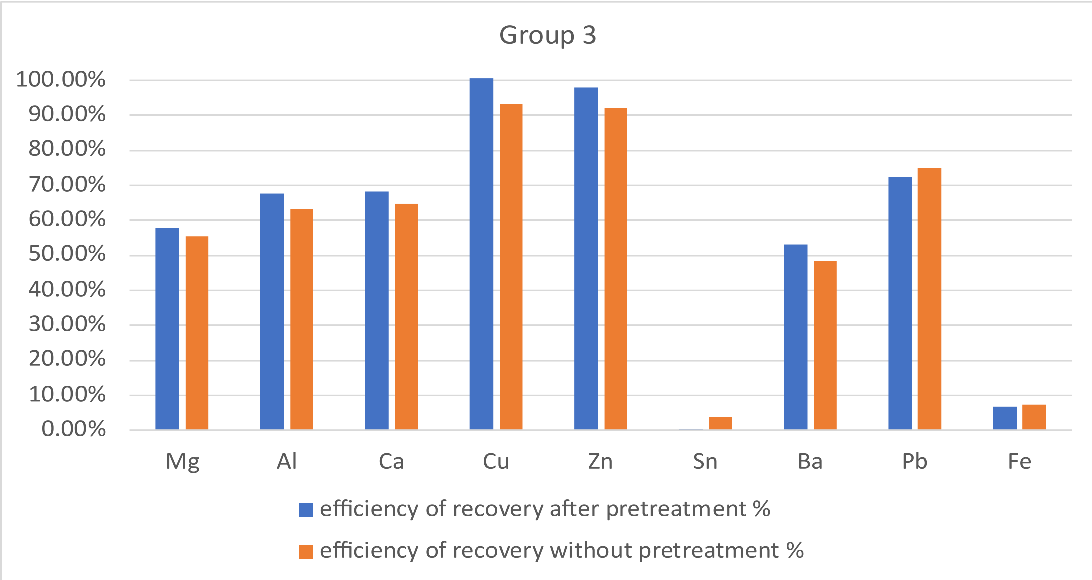
The liberation of materials does not only refer to copper as previously elaborated but also includes other metals and materials included in the PCBs. The ICP analysis of the samples comparing those which undergo solvent pre-treatment to those which are only subject to leaching shows that the trend of the other materials' recovery is analogous to that of copper. In Figure 29 (a), which shows the impact of solvent pre-treatment on Group 1, the efficiency of material recovery for barium, calcium, magnesium, and aluminium is doubled after the introduction of the solvent pre-treatment phase using DMSO. In the case of tin, a staggering 40 times increase is experienced. Moving to Group 2 with finer particle size, the improvements are major. In Figure 29 (b), barium, calcium, magnesium, and aluminium exhibit a 3-fold increase in their recovery while that of zinc doubles. Tin in Group 2 maintains the same dramatic 40-fold increase after solvent pre-treatment. Regarding Group 3, shown in Figure 29 (c), the improvements are less sharp showing the limited effect of solvent pre-treatment on the fine particle size. These trends are similar to those exhibited by copper under the various particle sizes and continue to question the viability of solvent pre-treatment for finer particles below 400 μm.


Group 1
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Mg
Al
Ca
Cu
Sn
Ba
efficiency of recovery after pretreatment %
efficiency of recovery without pretreatment %

(a)


Group 2
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Mg
Al
Ca
Cu
Zn
Sn
Ba
efficiency of recovery after pretreatment %
efficiency of recovery without pretreatment %

(b)



(c)

Figure 29: The impact of particle size on the improvement trends of material recovery (a) Group 1 with particle size between 8mm and 5.6mm, (b) Group 2 with particle size between 5.6mm and 2mm, (c) Group 3 with particle size less than 400 μm

5.3. Conclusion

In this chapter, the problem of material composition of PCBs was discussed intensively. To have a better understanding of the variations in material composition among the different categories of PCBs and the different models within the same category, 3 different categories were investigated: Motherboard, RAM, and CPU and chipset. The study explored the variation in both metal and non-metal content including the difference in the organic part and the results obtained offer a deep understanding of the structure of these PCBs. This outcome paves the way for a more efficient material recovery by customizing the recovery techniques based on the materials found in each category guided by the extended understanding of PCBs. Thus, changing our perspective on PCBs from generic to more specialized and focused. The results contribute to achieving a greener circular economy through the improvement of material recovery rates and the encouragement of urban mining as an alternative resource for materials specially those which are critical to the European economy as established by the EU Critical Raw Materials Act.

With the goal of providing optimised material recovery techniques and further supporting the EU Critical Raw Materials Act, the chapter explores the use of DMSO as a solvent pre-treatment phase before the leaching of materials from motherboard PCBs. By investigating different particle size groups, the impact of solvent pre-treatment is better understood, pre-treatment is always positive even if more favourable results can be obtained with particle sizes being in the range of 5.6mm and 2mm (Group 2). This particle size offers a good compromise to the need for extensive preparation of the PCBs in order to reach a powder state, as in the case of Group 3, thus, eliminating the health and environmental risks associated with the handling of fine powders. Additionally, by eliminating the need for pulverization, material loss is brought to a minimum contributing to better resource conservation which is also achieved from the time, energy and manpower spared from the performing of the pulverization stage.

Regarding to the improvements experienced by Group 1 and Group 3, they remain unsatisfactory. Since in the case of Group 1, the recovery efficiency of copper after the solvent pre-treatment is around 72.4% which leaves almost 28% of the copper content lost. In the case of Group 3 despite reaching 100% copper recovery rate with the introduction of the solvent pre-treatment phase, a 93% recovery rate could be achieved without the extra step of the solvent pre-treatment which raises the question of whether solvent pre-treatment for powders can be justified economically and environmentally given the extra use of chemicals and energy.

Finally, there remains a set of challenges that face solvent pre-treatment using DMSO. To begin with, the question of solvent recovery remains crucial, although not covered within the scope of this study. Since a closed loop system which allows the recovery and reuse of the solvent would contribute to making the process more economic and environmentally friendly. Despite the fact that the topic has been discussed in various research, a complete study that evaluates the end-to-end process starting from the solvent pre-treatment passing by material recovery through leaching reaching the solvent regeneration remains a gap to be addressed.

Moreover, the use of DMSO is frowned upon from the environmental point of view, despite being painted as a green solvent. This is currently being mitigated by other research which evaluates greener solvents such as ionic liquids. Yet, the effectiveness and economic viability remains questionable as the investigations are still in their early stage.

Finally, the effectiveness of solvent pre-treatment using DMSO is rarely investigated on an industrial scale. Pilot studies have been the topic of some limited studies; however, the complete evaluation of this treatment technique in the industry is still not addressed.

Nevertheless, the results obtained and discussed in this chapter remain valid and are a step closer towards the addressing of the highlighted challenges. The results, although obtained from the treatment of motherboard PCBs, are also valid for other types of PCBs since the structure is more or less the same. The study encourages better resource management and a more precise material tracking and recovery in addition to contributing to safer working environments and mitigating the impact of some of the hazards associated to WEEE handling.

Chapter 6

Conclusion

In this study, the issue of electronic waste was explored highlighting the unsustainable trends in the consumption of electronics and the subsequent generation of WEEE. This comes in a time when many raw materials are becoming more strategic and critical to find; calling for the exploitation of the otherwise lost opportunities related to the material recovery due to inefficient handling.

The problems discussed in this dissertation can be summarised in two main points. First, the complexity of the WEEE ecosystem which is spans across multiple domains rendering the handling process complex and sophisticated. The second problem is related to the use of generic data when handling different types of WEEE which leads to inaccurate assumptions and inefficient material recovery.

These two issues gave rise to the set of research questions and the objectives which guided this research. To begin with, the research investigates the possibility of development of a multi-domain ontology based DSS to simplify the complexity of the WEEE domain and promote informed decision-making aligned with a green circular economy. The DSS integrates the three critical three domains of WEEE that are usually disconnected and handled separately: technological domain, material domain, and hazard domain. The research dives deeper into evaluating the consolidation of knowledge from the three different domains while maintaining a scalable and reusable system. The objectives of the developed system were to simplify the WEEE domain and the decision-making process while promoting the availability of knowledge about WEEE.

The study then focuses on PCBs as a type of WEEE and attempts to address the research question regarding the differences in material structure among the different categories of PCBs and within the same category among the different model. This research question aimed to draw more accurate assumptions when handling PCBs and avoid the overgeneralization of the topic which leads to imprecise handling techniques and can cause losses in material recovery. To promote a greener circular economy, the research finally studies the impact of solvent pre-treatment using DMSO to handle PCBs specifically motherboard PCBs. The research assesses the impact of the particle size of the treated PCBs on the efficiency of material recovery.

The results obtained and discussed in this research satisfy the objectives and provide direct answers to the aforementioned research questions. Regarding the ontology-based DSS, the examples extracted from the model highlighted the potential of the DSS to simplify the domain and connect the three domains covered by the scope of the DSS in an efficient and rather straightforward manner, despite the ontology is initially focused on solar PVs as a POC. The methodology adopted for the development of the DSS, and the ontology prevents the DSS from derailing from the defined objectives and scope. The scalability and reusability of the ontology is another key feature discussed in the research. The developed ontology offers a wide range of features such as the object and data properties which allow the definition of concepts in multiple ways depending on the level of depth needed. This ensures that beyond the POC the ontology can grow to include the WEEE domain as a whole with no adjustments needed to the structure of the ontology. The proposed design for the GUI complements the DSS as a solution to a complex issue by helping maintain the DSS user-friendly and eliminating the need for domain experts or specific skills to use the DSS.

As for the PCB investigation, the study concluded that there are significant differences in the material content of different types of PCBs nonetheless the overall composition remains the same. This was reached by analysing three types of PCBs: motherboards, RAMs, and CPU and chipsets. The analysis was carried out on different models of the same category and the results were compared among the same category to understand the extent of variation in material composition within the same category. Based on this analysis trends were also drawn between the year of production and the different materials found in the PCBs. The overall composition of materials was then compared between the different categories analysed and it was established that copper, silicon, calcium and aluminium dominate all three categories analysed. Thus, when targeting these materials, all three categories can be treated equally. The study also found that CPU and chipsets contain significant amounts of some materials such as gold, silver and lead compared to the other two categories of PCBs analysed. Finally, the content of organic component was investigated for all three categories which showed that both motherboards and RAM have a relatively similar organic composition at around 25%. However, that of CPUs and chipsets is quite different experiences strong fluctuations.

After the deeper understanding provided by the PCB analysis, the effect of solvent pre-treatment using DMSO, and the impact of the particle size on the efficiency of material recovery is discussed. The results show that DMSO treatment before leaching have a favourable outcome on liberating the materials from the organic component. The particle size group which corresponds to the highest achieved improvement is between 5.6mm and 2mm (Group 2) with copper recovery rates reaching 87.65%. Copper recovery rates of 100% were achieved with particle size less than 400µm and with a pre-treatment phase. Yet, the increase is not justifiable since a yield of 93.24% can be achieved without the pre-treatment phase. The results show that other metals such as barium, calcium, magnesium, and aluminium experience a significant increase in their recovery rate at particle size between 5.6mm and 2mm after the introduction of the solvent pre-treatment phase.

The above discussed results satisfy the research objectives and provide a deeper understanding of the WEEE domain and the potential handling techniques which further support the ongoing research in the field.

Publications and Dissemination Activities

Peer-Reviewed Articles

- Mohamed, A.T.I.; Schimperna, G.; Cantoni, G.; Demichelis, F.; Fino, D.; Perucchini, S.; Rubertelli, F.; Laviano, F. Effect of Solvent Pre-Treatment on the Leaching of Copper During Printed Circuit Board Recycling. *Recycling* **2025**, *10*, 80. https://doi.org/10.3390/recycling10030080

- Ismail Mohamed AT, Laviano F, Fino D, Rubertelli F and Toscano C (2025) A sustainable approach tackling WEEE management using ontology-based DSS. *Front. Sustain*. 6:1523114. doi: 10.3389/frsus.2025.1523114

Conference Presentations

- A. Tarek, *The Use of Decision Support Systems for The Handling of E-Waste in a Circular Economy*, Presented at the 11th International Conference on Sustainable Solid Waste Management, Rhodes, Greece, June 2024

- A. Tarek, *The Upcycling of Treated Printed Circuit Boards Into an Innovative Material Block Within The Scope of Zero Waste And Circular Economy.* Presented as a Poster at the 32nd International Materials Research Congress, Cancun, Mexico, August 2024

Workshops

- Attended the Current Trends in Thin Film Photovoltaics: From Classical to Emerging Technologies workshop at the 32nd International Materials Research Congress, Cancun, Mexico, August 2024

- Attended the Circular Economy Priorities conference, Brussels, Belgium, December 2024

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