POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering



Master's Degree Thesis

Recovery of Copper and Aluminium from WEEE Recycling Streams by Electrostatic Separation

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Abstract

Waste Electrical and Electronic Equipment (WEEE) represents a complex waste stream containing valuable materials such as copper, aluminium, iron, plastics and electronic components. The recovery of non-ferrous metals from WEEE is important from both environmental and economic points of view, but it is often challenging because real industrial fractions are heterogeneous and contain particles with different sizes, shapes and material compositions.

This thesis examines the recovery and concentration of copper and aluminium from two industrial WEEE-derived streams using manual characterization, sieving and electrostatic separation. The samples were obtained from the treatment streams of refrigerators and small electrical devices.

The main experimental stream was a copper/aluminium-rich fraction related to the refrigerator recycling line. This material was manually characterized, subsampled by riffle splitting and processed using a laboratory electrostatic separator under different operating conditions. The results showed that the separation performance depended strongly on drum frequency. At 30 kV and 40 Hz, the copper-rich product had a copper purity of 10.49% and a copper recovery of 67.16%. Increasing the frequency to 60 Hz improved copper purity to 29.94% and copper recovery to 71.48%. At 70 Hz, the highest copper purity was obtained, 57.81%, but copper recovery decreased to 64.88%.Re-processing of the intermediate Bin 1 product from the 60 Hz test produced a smaller copper-rich fraction with 42.30% copper purity, showing that part of the copper in the intermediate product could be further concentrated by a second separation pass.

The initial electrostatic separation tests showed that changing the machine parameters alone was not sufficient to obtain a fully satisfactory separation. For this reason, particle size classification by sieving was introduced as a feed-preparation step for the same refrigerator-derived Cu/Al fraction. Selected fine size fractions were then processed separately by electrostatic separation at 30 kV, 60 Hz and 10% feeder.The finest fraction, smaller than 6.3 mm, produced the best copper-rich product, with 75.12% copper purity and 74.29% copper recovery. Under the same operating conditions, the larger fine fractions produced lower copper purities, indicating that particle size affected the separation result.

A second industrial stream, obtained from small electrical devices, was used for manual characterization. This sample was more heterogeneous and contained aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material, including wires, capacitors and mixed copper–aluminium pieces. Due to the large size, irregular shape and complexity of several components, this sample was not processed by sieving or electrostatic separation using the available laboratory equipment.

Under the tested conditions, electrostatic separation increased the copper concentration in the refrigerator-derived Cu/Al fraction. However, adjustment of the machine settings alone did not provide a sufficiently clean separation. The clearest improvement was obtained after particle size classification, while re-processing Bin 1 produced an additional copper-rich fraction. The small electrical devices sample could not be treated in the same way because several components were too large, irregular or composite for the available laboratory equipment. The comparison between the two samples therefore showed that the suitability of a separation method depended on the physical condition and processability of the feed.

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Chapter 1

Introduction

1.1 Background

Waste Electrical and Electronic Equipment (WEEE) includes many different discarded products, ranging from large household appliances to small electronic devices. Their composition varies considerably and may include metals, plastics, glass, printed circuit boards, cables, refrigerant gases, oils and other components that require different treatment steps. The continuous replacement of electrical and electronic equipment has increased the amount of WEEE generated, making its correct management an important environmental and industrial issue.[1, 2]

WEEE is also an important secondary source of valuable materials. Depending on the type of equipment and the treatment stage, recovered fractions may contain aluminium, copper, iron, plastics and, in some cases, precious metals associated with printed circuit boards. Recovering these materials supports circular economy strategies by reducing demand for primary raw materials and increasing the value of recycled streams.[1]

In industrial WEEE treatment plants, different waste categories are usually managed through dedicated processing routes. During the plant visit carried out within this work, several material streams were observed, including the refrigerator recycling stream and the small electrical devices stream. The plant also referred to operational WEEE categories such as R1 for refrigeration equipment, R2 for large household appliances, R3 for screens and televisions, R4 for small electrical and electronic devices, and R5 for lamps. Among these streams, the experimental work of this thesis mainly focused on two fractions: a copper/aluminium-rich fraction related to the refrigerator treatment line, and a second sample obtained from small electrical devices.

1.2 Industrial and Technical Context

Refrigerators require a dedicated treatment route because they contain a combination of refrigerant gases, oils, polyurethane foam, metals and plastics. During the plant visit, the process started with the manual removal of components such as glass, rubber parts, capacitors and electronic boards. Oil and refrigerant gases were then extracted before the refrigerator bodies entered the mechanical treatment line. After shredding, the material was separated into ferrous metals, non-ferrous metals, plastics and polyurethane-derived fractions.

One of the non-ferrous outputs from the refrigerator treatment line contained both aluminium and copper. Separating these two metals is more difficult than separating metals from non-metals because both are electrically conductive. This was the main reason for selecting electrostatic separation in this work, with the aim of concentrating copper from the aluminium-rich industrial fraction.

The refrigerator-derived Cu/Al fraction was the main material used in the laboratory work. It was first characterized manually and then tested with the electrostatic separator under different operating conditions. These initial tests did not produce a sufficiently clean separation by changing the machine settings alone. The same material was therefore sieved into narrower size ranges, and selected fractions were tested separately to examine the influence of particle size on the separation result.

The second industrial sample came from the small electrical devices stream. Compared with the refrigerator-derived Cu/Al fraction, this material was much more heterogeneous. During manual sorting, aluminium, copper, printed circuit boards, plastics and batteries could be separated, while wires, capacitors, mixed copper–aluminium pieces and other small heterogeneous components were grouped as mixed/residue material. The sample was not sieved or processed with the electrostatic separator because many of its components were too large, irregular or composite for the available laboratory equipment. The work on this stream was therefore limited to manual sorting and weighing of the main material categories.

1.3 Research Motivation

The motivation for this work developed from the results of the first laboratory tests on the refrigerator-derived Cu/Al fraction. Changing the voltage and drum frequency affected the collected products, but the separation remained inconsistent. The feed contained particles with different sizes, shapes and degrees of liberation, and these differences influenced the way the particles moved inside the separator.

It became clear during the tests that adjustment of the machine settings alone

would not be sufficient. The same Cu/Al material was therefore divided into narrower particle-size fractions by sieving. Testing selected fractions separately made it possible to compare their separation behaviour and to examine the relationship between particle size, copper purity and copper recovery.

The small electrical devices sample could not follow the same experimental route. Its larger, irregular and composite components were not suitable for the available sieving and electrostatic separation equipment. This difference between the two samples showed that the choice of a separation method must also take account of the physical condition of the material, not only the type of technology being used.

1.4 Aim and Objectives

The main aim of this thesis was to examine how electrostatic separation and feed preparation affected the recovery and concentration of copper and aluminium from two industrial WEEE-derived streams.

The specific objectives were:

- To describe the main treatment stages observed during the WEEE recycling plant visit, with particular attention to the refrigerator line and the small electrical devices stream.
- To characterize the copper/aluminium-rich fraction obtained from the refrigerator recycling line.
- To investigate the influence of applied voltage and drum frequency on copper purity and copper recovery during electrostatic separation.
- To assess whether re-processing an intermediate output fraction could recover and concentrate additional copper.
- To use sieving as a feed-preparation step for the refrigerator-derived Cu/Al fraction and divide the material into different particle-size classes.
- To compare the electrostatic separation results of selected sieved fractions in terms of copper purity and copper recovery.
- To manually characterize the small electrical devices sample by separating and weighing aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material.
- To explain why the small electrical devices sample was not suitable for sieving and electrostatic separation with the available laboratory equipment.
- To identify the main factors that influenced the separation results and suggest improvements for future laboratory or industrial work.

1.5 Scope of the Work

The samples used in this study were collected from an industrial WEEE recycling plant. During the plant visit, the incoming waste was handled through separate treatment streams according to the type of equipment and the treatment required. This classification was used to identify the two streams selected for the laboratory work.

Figure 1.1 shows the two plant streams selected for this study. The Cu/Al-rich fraction was obtained from the refrigerator treatment line. The second sample came from the small electrical devices stream and was selected for manual characterization because of its heterogeneous composition.

Most of the laboratory work was carried out on the refrigerator-derived Cu/Al fraction. Manual sorting was first used to determine its main composition, after which the sample was divided by riffle splitting. The material was then tested with the electrostatic separator at different operating settings. One intermediate output was processed for a second time, and the remaining material was later divided into particle-size classes by sieving. Selected fine fractions were subsequently tested separately with the electrostatic separator.

The small electrical devices sample followed a different experimental route. It contained larger, irregular and composite components and could not be prepared for the available sieving and electrostatic separation equipment. The sample was therefore sorted manually, and the main material categories were weighed separately. This provided a basic characterization of the stream and showed why the same separation procedure used for the refrigerator-derived Cu/Al fraction could not be applied.

Figure 1.2 summarizes the main steps followed during the experimental work. The two samples did not follow the same route. The refrigerator-derived Cu/Al fraction was manually characterized, tested under different separator settings and later divided into particle-size classes. Selected sieved fractions were then tested separately. The small electrical devices sample was limited to manual sorting and weighing because many of its components were not suitable for the available laboratory equipment. The workflow also shows how the experimental procedure was adjusted after the initial electrostatic separation tests, when particle size was identified as an important factor affecting the separation result.

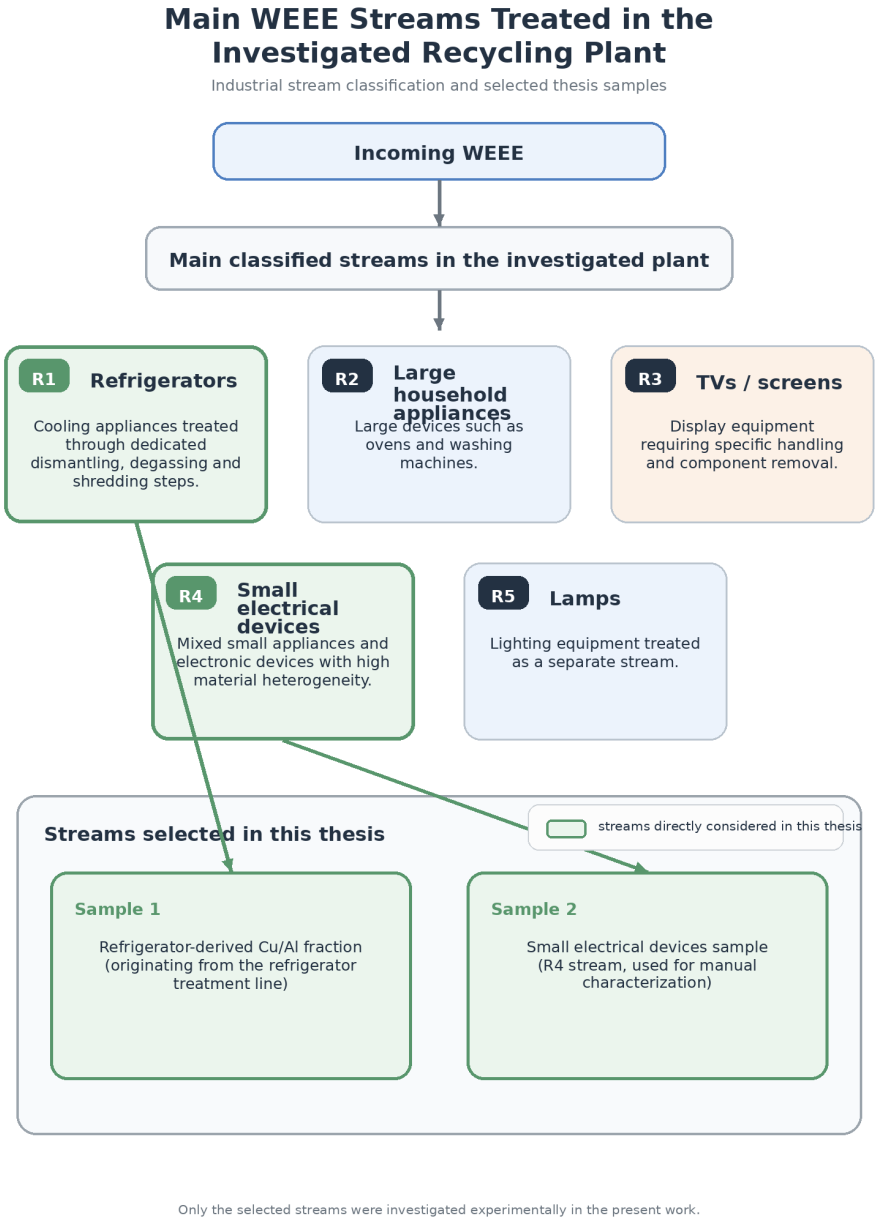


Figure 1.1: Schematic representation of the main WEEE streams treated in the investigated recycling plant and identification of the streams relevant to the present thesis. *Source: author's elaboration.*

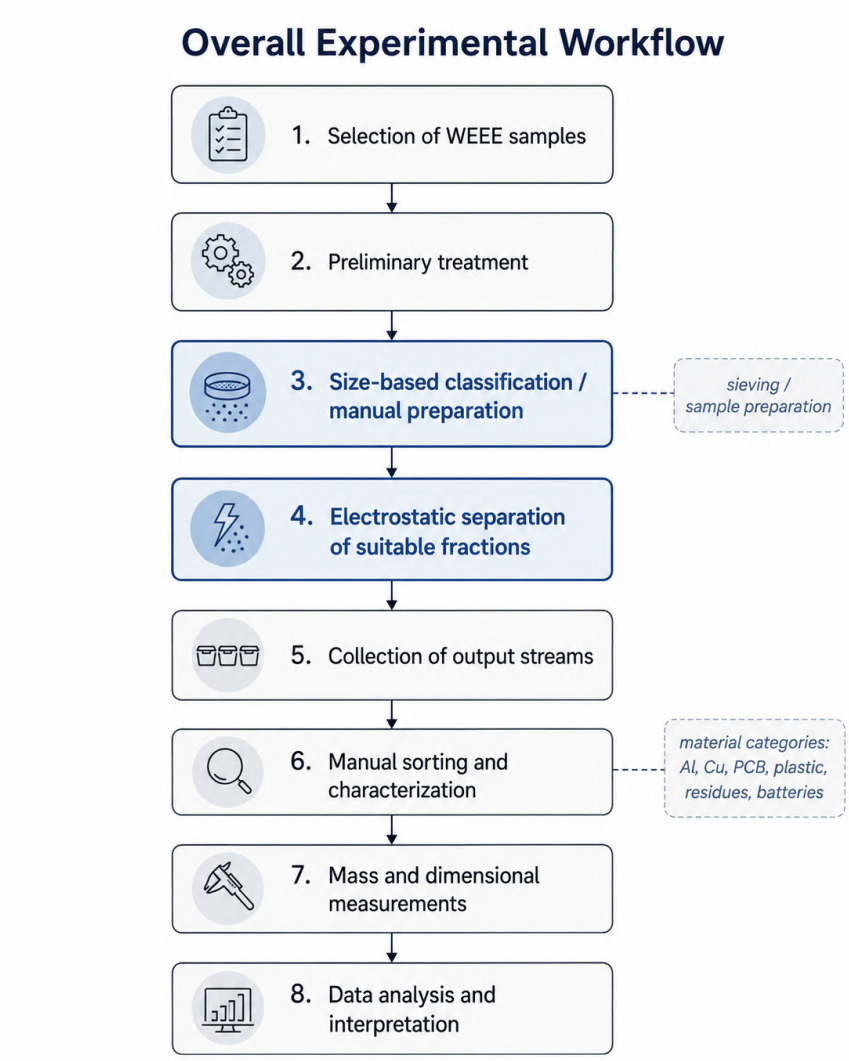


Figure 1.2: Overall experimental workflow adopted in this study for the treatment, separation and characterization of WEEE samples. *Source: author's elaboration.*

1.6 Structure of the Thesis

The thesis is organized into six chapters.

Chapter 1 introduces the background of WEEE recycling, the industrial context, the motivation of the work, the main objectives and the scope of the study.

Chapter 2 presents the literature review, focusing on WEEE treatment, physical separation technologies, electrostatic separation, copper and aluminium recovery, and the role of particle size in separation efficiency.

Chapter 3 describes the industrial case study, including the recycling plant visit, the refrigerator recycling stream, the small electrical devices stream and the industrial origin of the material fractions selected for the laboratory work.

Chapter 4 presents the materials and methods used during the laboratory activity. It describes the characterization of the refrigerator-derived Cu/Al fraction, riffle splitting, electrostatic separation tests, re-processing, sieving of the Cu/Al fraction, and the manual characterization of the small electrical devices sample.

Chapter 5 reports and discusses the experimental results. The first part is dedicated to the refrigerator-derived Cu/Al fraction, including the initial electrostatic tests, re-processing and the effect of particle size classification on separation performance. The second part presents the manual characterization of the small electrical devices sample and compares the two industrial streams.

Chapter 6 summarizes the main conclusions of the work and provides recommendations for future improvements.

Chapter 2

Literature Review

2.1 Waste Electrical and Electronic Equipment

Waste Electrical and Electronic Equipment (WEEE), often referred to as e-waste, includes discarded electrical and electronic products together with their components. Its composition varies considerably according to the type, function and age of the equipment, as well as the dismantling and pre-treatment operations carried out before material recovery. Depending on the stream being processed, WEEE may contain ferrous and non-ferrous metals, plastics, glass, printed circuit boards, cables, oils, refrigerant gases and hazardous substances [1, 3].

This variability is particularly important when practical recycling operations are considered. Chancerel and Rotter characterized approximately 700 individual small electrical and electronic appliances and found considerable differences in mechanical properties and material composition, not only between different equipment types but also between individual products belonging to the same category [4]. This means that a treatment procedure suitable for one WEEE sample may not necessarily be suitable for another sample classified within the same general stream.

WEEE requires careful management for both environmental and resource-related reasons. Incorrect handling may release hazardous substances and create risks for human health and the environment. At the same time, discarded equipment contains recoverable materials such as copper, aluminium, iron, precious metals and polymers. Recycling therefore combines waste management with the recovery of secondary raw materials.

The diversity of the plastic fraction provides a further example of the complexity of WEEE. Martinho et al. directly examined approximately 3400 items in a WEEE recycling facility, including cooling appliances and small electrical devices. Their results showed the presence of several polymer types and identified practical difficulties in material identification and manual sorting [5]. Similar variability was

observed in the small electrical devices sample examined in the present work.

Copper and aluminium are particularly relevant to this thesis. Copper is commonly used in wires, motors, connectors and printed circuit boards because of its high electrical conductivity. Aluminium is found in frames, heat exchangers, structural parts and other lightweight components. Both metals have economic value, but their recovery becomes more difficult when they remain together in mixed or shredded industrial fractions.

2.2 WEEE Categories and Treatment Streams

WEEE streams are commonly separated according to the type of equipment and the treatment they require. In the industrial context considered in this study, the main streams were identified as R1 to R5. R1 includes refrigeration and temperature-exchange equipment, such as refrigerators and freezers. R2 refers to large household appliances, including washing machines and ovens. R3 covers televisions and screens, R4 includes small electrical and electronic devices, and R5 is associated with lamps.

The treatment route changes from one stream to another because the incoming equipment differs in composition, dimensions and components requiring dedicated handling. Refrigerators contain oils, refrigerant gases and polyurethane insulation, which must be managed before or during mechanical treatment. Ruan and Xu described an automated refrigerator-cabinet recovery line combining closed size-reduction operations, treatment of the released refrigerant, air-current separation, magnetic separation and eddy current separation [6]. Their study illustrates why refrigerator recycling requires a sequence of connected treatment and separation operations rather than a single mechanical step.

Small electrical devices present a different processing problem. They may contain printed circuit boards, cables, plastic housings, batteries, metallic parts and several small electronic components. Their composition can also vary considerably between individual products, even when the products are assigned to the same general category [4]. Depending on their dimensions and degree of dismantling, treatment may involve manual sorting, component removal, shredding and subsequent physical separation.

Two of these industrial streams were used in the present work. The main experimental material came from the refrigerator treatment line and consisted of a non-ferrous fraction containing copper and aluminium. This fraction was selected for the electrostatic separation tests because both metals remained together after the preceding industrial treatment stages and could not be separated through a simple metal/non-metal separation step.

The second sample came from the small electrical devices stream. It contained printed circuit boards, wires, metallic pieces, plastics, batteries and other mixed electronic components. Many of these components were larger, irregular or composite and could not be prepared for the available laboratory sieving and electrostatic separation equipment. This sample was therefore manually sorted and weighed, whereas the refrigerator-derived Cu/Al fraction was used for particle-size classification and electrostatic separation tests.

2.3 Physical Separation Technologies in WEEE Recycling

Industrial WEEE treatment generally starts with a combination of manual and mechanical pre-treatment. Components requiring separate or dedicated handling are removed first, while the remaining material may then be shredded, screened and directed to different physical separation stages according to its composition and condition [7, 8].



Figure 2.1: Generalized mechanical and physical treatment sequence for WEEE before material recovery. The sequence is presented as a simplified overview and may vary according to the type and condition of the incoming waste stream. *Source: author's elaboration based on[7, 8].*

Figure 2.1 illustrates that WEEE processing normally involves several connected operations rather than a single separation step. Manual dismantling, size reduction, screening and physical separation are combined according to the composition and

physical condition of the incoming material. These operations are used to liberate components, control the particle-size distribution and concentrate materials with different physical properties [7, 8].

Mechanical and physical separation methods are commonly applied after dismantling and shredding. Depending on the equipment used, separation may be based on particle size, density, magnetic response, electrical conductivity or particle shape. The effectiveness of each method depends not only on the material type but also on the degree of liberation and the physical condition of the feed [7, 8].

Magnetic separation is generally applied at an early stage to remove ferrous materials such as iron and steel from shredded WEEE. These materials respond strongly to a magnetic field and can therefore be separated from the non-magnetic fraction. After this stage, the remaining material may still contain aluminium, copper, plastics, glass and other non-ferrous or non-metallic components [7, 8].

Eddy current separation is used mainly to recover non-ferrous metals from non-metallic materials. A rapidly changing magnetic field induces electrical currents in conductive particles, producing a repulsive force that changes their trajectory. Aluminium and copper particles can therefore be separated from materials such as plastics or glass. However, the separation result is influenced by the operating conditions and by particle properties such as size, shape and mass.

Ruan et al. investigated the recovery of aluminium particles from crushed waste refrigerator cabinets using eddy current separation. They reported that feeding speed, the relative motion between the magnetic field and the particles, and particle characteristics influenced the separation efficiency [9]. Their findings show that the performance of a physical separator cannot be evaluated independently of the condition and presentation of the feed.

Although eddy current separation can recover conductive non-ferrous particles from non-metallic materials, it is less suitable for obtaining a clean separation between copper and aluminium because both metals are electrically conductive. For the refrigerator-derived fraction investigated in this thesis, a method capable of producing different particle trajectories within a conductive metal mixture was therefore required. Electrostatic separation was selected for this purpose and is discussed in the following section.

2.4 Electrostatic Separation

Electrostatic separation is a dry process in which particles are separated according to their electrical behaviour. The charging mechanism depends on the design of the separator and may involve corona discharge, induction, triboelectric charging or contact with an electrically active surface. After charging, conductive and non-conductive particles respond differently to the electric field and follow different

paths. The method generally works best when the feed is dry, granular and sufficiently liberated.

The performance of electrostatic separation is controlled by a combination of equipment settings and feed characteristics. The applied voltage determines the strength of the electric field and affects particle charging, while the rotational speed of the grounded roll influences the residence time of the particles and the point at which they leave the roll surface. The feeding conditions also affect the distribution of the material over the roll and may influence the stability of the separation process.

These variables should not be considered independently. Jiang et al. performed 32 experiments on a roll-type corona-electrostatic separator using crushed PCB material in the particle-size range of 0.30–0.45 mm. Their results showed that the masses of the conductor, non-conductor and middling products were influenced both by the individual operating variables and by interactions between them [10]. This indicates that changing one operating parameter may modify the effect of another and that separator performance should therefore be evaluated under a defined combination of settings.

In addition to the operating conditions, the physical characteristics of the particles influence their movement in the electric field. Lu et al. compared metal particles having spherical, cylindrical and flake-like shapes and found that the predicted and experimental trajectories differed according to particle geometry. Under the investigated conditions, spherical particles were projected farther than cylindrical particles, whereas flake-like particles followed shorter trajectories [11]. Particle shape must therefore be considered together with particle size, mass and electrical behaviour when interpreting electrostatic separation results.

This aspect is particularly relevant for industrial WEEE-derived materials. Unlike laboratory mixtures prepared from particles with relatively controlled dimensions and shapes, shredded industrial fractions may contain wires, flakes, curved pieces and partially liberated composite particles. Consequently, particles of the same material may not necessarily follow identical trajectories, even when the separator is operated under constant settings.

Previous studies have shown that electrostatic separation can be effective for recovering metals from WEEE fractions. For example, Salama et al. investigated the distinct recovery of copper and aluminium from waste electric wires using a roll-type electrostatic separator [12]. Other studies focused on aluminium recovery from cable recycling residues [13], metal and non-metal separation from printed circuit boards [14], and copper recovery from pretreated shredder residues [15]. These works confirm that electrostatic separation is a promising technique, but they also show that separation efficiency strongly depends on both feed preparation and separator settings.

2.5 Copper and Aluminium Recovery

Copper and aluminium are among the main non-ferrous metals recovered from WEEE. Copper is commonly found in wires, motor windings, connectors and printed circuit boards, while aluminium is often present in structural parts, housings and heat exchangers. Both metals have economic value and may occur together in the same non-ferrous output after mechanical treatment.

Separating copper from aluminium is more difficult than a conventional metal/non-metal separation because both materials are electrically conductive. Their response in electrostatic or eddy current systems may therefore overlap. The final trajectory of a particle is influenced not only by conductivity, but also by its mass, size, shape, surface condition and degree of liberation. These factors become especially important when the feed contains irregular or partly composite particles.

The condition of the feed has a direct effect on the quality of the recovered fractions. A wide particle-size distribution can reduce separation selectivity because small and large particles do not move in the same way inside the separator. Irregular shapes, attached residues and mixed copper–aluminium pieces may also increase contamination between the collected products. In practice, operating conditions that produce a highly concentrated copper fraction do not always recover the largest possible amount of copper. Copper purity and copper recovery must therefore be considered together when evaluating the separation result.

The reviewed studies demonstrate that electrostatic separation is affected by separator configuration, operating conditions and particle characteristics. However, many previous investigations were performed using crushed PCB material or mixtures prepared within controlled particle-size ranges. The material examined in the present study was instead a real industrial Cu/Al fraction obtained from a refrigerator treatment line. It contained conductive particles with irregular sizes, shapes and degrees of liberation. For this reason, the experimental programme considered not only the machine settings but also re-processing and particle-size classification as possible approaches for improving the separation performance.

2.6 Effect of Particle Size on Electrostatic Separation

Particle size can affect the behaviour of a material during electrostatic separation. Although electrical conductivity is important, it is not the only property controlling the trajectory of a particle. Particle mass, surface area, shape, degree of liberation and contact with the rotating drum may also influence where the particle is collected. Particles made from the same material may therefore behave differently when their dimensions or shapes are different. [14, 15]

This is particularly relevant for fractions obtained from industrial WEEE treatment. Unlike prepared laboratory mixtures, these materials may contain wires, flat aluminium pieces, copper fragments, attached plastic and partly liberated components. When particles with very different sizes are processed together, they may respond differently to the electric field and drum rotation. Some valuable particles may then report to an intermediate or incorrect collection bin rather than to the expected product.

Sieving can be used to reduce this variation before separation. Dividing the feed into narrower particle-size classes produces fractions that are more comparable in terms of particle size and mass. This does not remove the influence of shape, surface condition or incomplete liberation, but it makes the behaviour of the feed easier to evaluate. Previous studies have also reported that particle size and shape can influence the performance of electrostatic and related physical separation processes. [16]

This point became relevant during the experimental work on the refrigerator-derived Cu/Al fraction. The first tests were carried out on material with a broad particle-size distribution. Adjusting the voltage and drum frequency changed the separation result, but did not produce a sufficiently clean copper-rich fraction. The remaining material was therefore sieved, and selected fine fractions were tested separately under the same operating conditions. This allowed the effect of particle size to be examined without changing several machine parameters at the same time.

Particle-size classification was not applied to the small electrical devices sample. That material contained larger, irregular and composite components that were not suitable for the available sieves or electrostatic separator. Its characterization was therefore limited to manual sorting and weighing of the main material categories.

2.7 Purity and Recovery

Two indicators were used to evaluate the electrostatic separation results in this study: copper purity and copper recovery. Copper purity describes the proportion of copper in a selected output product. Copper recovery shows how much of the copper initially present in the feed was transferred to that product. The equations used to calculate these indicators are presented in Chapter 4.

These indicators describe different aspects of the separation. A high copper purity means that the selected product contains relatively little aluminium or residue. However, this does not necessarily mean that most of the available copper was recovered. A small product containing mainly copper may have high purity but still represent only a limited part of the copper present in the original feed.

The opposite situation is also possible. A large amount of copper may be

collected in one output, resulting in high recovery, while aluminium and other materials collected in the same bin reduce its purity. Purity and recovery were therefore considered together when comparing the operating conditions, the sieved particle-size fractions and the re-processing of the intermediate product.

2.8 Summary of the Literature Review

WEEE streams contain materials with very different physical and electrical properties, so their treatment normally requires several connected operations. Manual sorting, size reduction, screening and physical separation may all be needed before useful material fractions can be recovered. For the present work, the main technical difficulty was the separation of copper and aluminium when both metals were present in the same conductive fraction.

The studies reviewed in this chapter show that electrostatic separation can be used to concentrate materials from WEEE-derived streams, but the machine settings are only part of the process. Applied voltage, drum frequency and feed rate affect the movement of particles, while particle size, shape, surface condition and degree of liberation affect how individual particles respond inside the separator. This helps explain why a mixed industrial feed may not produce a clean separation even when the operating conditions are adjusted.

Particle-size classification was therefore relevant to the experimental approach used in this thesis. Sieving the refrigerator-derived Cu/Al material into narrower size ranges reduced one source of variation and allowed selected fractions to be tested separately. The small electrical devices sample required a different approach because its larger, irregular and composite components were not suitable for the available sieving and electrostatic separation equipment. Manual sorting and weighing were more appropriate for that stream.

These points provide the background for the industrial case study in Chapter 3, the experimental methods described in Chapter 4 and the interpretation of the results in Chapter 5.

Chapter 3

Industrial Case Study: WEEE Recycling Plant

3.1 Overview of the Plant Visit

The industrial visit was carried out at Transistor S.r.l., a company involved in the treatment of Waste Electrical and Electronic Equipment (WEEE), commonly referred to as RAEE in the Italian context. The plant is located in the metropolitan area of Turin.

The visit focused on the main stages used to receive, classify and process different WEEE streams. Particular attention was given to the refrigerator treatment line and the small electrical devices stream because these two areas were directly connected to the samples later examined in the laboratory.



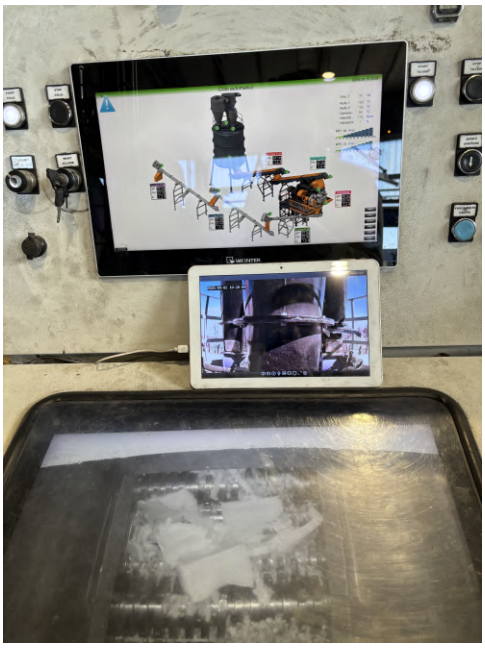
(a) General view of the recycling line.



(b) Feed/conveyor section of the plant.



(c) Processing equipment.



(d) Control and monitoring panel.

Figure 3.1: General overview of the refrigerator recycling plant observed during the industrial visit. *Source: photograph taken by the author during the visit to Transistor S.r.l.*

During the visit, different parts of the plant were observed, including the material feeding system, processing equipment, control panel and areas used for collecting the separated outputs. These observations helped clarify how the incoming waste was directed through different treatment routes before the final material fractions were produced.

Several WEEE streams were observed or discussed, including refrigeration equipment, large household appliances and small electrical and electronic devices. The treatment route was not the same for every stream because the equipment differed in size, composition, hazardous components and recoverable materials.

Two streams were directly relevant to the experimental work. The refrigerator treatment line produced a non-ferrous fraction containing copper and aluminium, which was later used for the electrostatic separation tests. The small electrical devices stream provided a more heterogeneous sample containing metallic pieces, plastics, wires, printed circuit boards and other mixed components.

The samples were collected from actual industrial treatment streams rather than prepared as controlled laboratory mixtures. Their particle sizes, shapes and levels of material liberation were therefore irregular and reflected the previous dismantling, shredding and separation stages. This made the samples more representative of practical recycling conditions, although it also introduced greater variation into the laboratory results.

3.2 General Organization of the Plant Activity

The plant handled different WEEE streams through separate treatment routes. Incoming equipment was first identified and classified according to the type of device. It was then directed to the appropriate processing area. This initial classification was necessary because the streams differed in size, composition, recoverable materials and the components requiring separate handling.

Before mechanical treatment, selected components were removed manually or handled through dedicated operations. In the refrigerator line, particular attention was given to oils, refrigerant gases and components that could not enter the main shredding stage directly. Small electrical devices presented a different mixture, which could include batteries, capacitors, printed circuit boards, wires and plastic housings.

After the preliminary treatment, the remaining material was reduced in size to release the different components. Magnetic separation was used to recover ferrous metals, while further physical separation stages produced non-ferrous, plastic and residual fractions. The composition and quality of these outputs depended on both the incoming equipment and the effectiveness of the earlier dismantling and mechanical treatment stages.

The refrigerator treatment line produced a non-ferrous output in which copper and aluminium were still present together. Although the industrial process had already separated this material from several other components, an additional separation step was required to obtain a more concentrated copper fraction. This output became the main material used for the laboratory electrostatic separation and particle-size classification tests.

3.3 RAEE Groups Considered in the Industrial Context

During the plant visit, the incoming equipment was identified according to the RAEE group to which it belonged. This classification helped distinguish the different treatment routes and clarified the industrial origin of the samples used in the laboratory work.

The groups most relevant during the visit were R1, R2 and R4. The R1 group includes refrigeration and temperature-exchange equipment, such as refrigerators, freezers and air-conditioning units. These products require dedicated treatment because they may contain refrigerant gases, oils and insulation foam. The R2 group covers large household appliances, including washing machines, dishwashers and ovens. The R4 group contains a more varied range of small electrical and electronic devices, including small household appliances, information technology equipment and mobile devices.

Only the R1 and R4 streams were selected for further study. The refrigerator treatment line produced a non-ferrous fraction in which copper and aluminium were still mixed after the industrial processing stages. This material became the main feed for the laboratory electrostatic separation tests.

The sample collected from the R4 stream had a different physical condition. It contained metals, plastics, wires, printed circuit boards and other electronic components with a wide range of sizes and shapes. Because it could not be processed with the same laboratory procedure as the refrigerator-derived fraction, it was examined through manual sorting and weighing.

3.4 Refrigerator Recycling Stream

The refrigerator treatment line required a controlled sequence of operations because the incoming appliances contained refrigerant gases, oils, polyurethane foam, metals, plastics and electrical components. These materials could not all be introduced directly into the mechanical treatment stage.

During the visit, the process began with the removal of components that required separate handling. Glass, rubber parts, capacitors, electronic boards and other

removable elements were taken out where necessary. The cooling circuit and compressor were also treated before shredding so that the oil and refrigerant gases could be extracted and managed separately.



(a) Rear part of the refrigerator before depollution-related operations.



(b) Tool used for depollution-related handling of the cooling circuit.

Figure 3.2: Preliminary treatment and depollution-related operations performed before the mechanical processing of refrigerators. *Source: photographs taken by the author during the visit to Transistor S.r.l.*

After the preliminary treatment and depollution stages, the refrigerator bodies were transported to the mechanical processing area. They were fed by conveyor into the shredding unit, where their size was reduced and the different materials were released from the original appliance structure.

The shredded mixture then passed through a series of separation stages. Ferrous metals were recovered first, while later stages produced non-ferrous metals, plastics and polyurethane-rich fractions. The quality of these outputs depended on how effectively the components had been removed and liberated during the earlier stages.



Figure 3.3: Mechanical treatment stage of the refrigerator recycling line, showing the conveyor feeding the shredding unit used for size reduction of the incoming appliances. *Source: photograph taken by the author during the visit to Transistor S.r.l.*

The material selected for the main laboratory experiments was obtained from one of the non-ferrous outputs of this treatment line. It consisted mainly of aluminium and copper particles, together with a smaller amount of residue and impurities. Although the plant process had already removed several other material groups, copper and aluminium were still present together in this fraction.

Further separation of these two metals was not straightforward because both copper and aluminium are electrically conductive. Their response could therefore overlap in separation systems designed mainly to distinguish conductive from non-conductive materials. The laboratory tests examined whether the copper content

of this industrial fraction could be increased using electrostatic separation.

The sample was first sorted and weighed manually to determine its aluminium, copper and residue contents. riffle splitting was then used to prepare representative portions for the separator tests. The initial experiments compared different voltage and drum-frequency settings. One intermediate output was also processed for a second time to determine whether part of the copper remaining in that product could be further concentrated. The later particle-size classification tests are described in Chapter 4.

3.5 Small Electrical Devices Stream

The second industrial sample was collected from the small electrical devices stream. Unlike the refrigerator-derived Cu/Al fraction, this material was not a relatively uniform mixture of liberated metal particles. It contained metallic pieces, printed circuit boards, wires, plastic components, batteries and other mixed electrical and electronic parts.

During the plant visit, several materials associated with this stream were observed, including cable-rich fractions, power supply units, hard disks, small motors and printed circuit boards. Their dimensions, shapes and compositions varied widely, reflecting the different types of equipment entering the same treatment stream.

In the laboratory, the sample was separated manually into the main material categories, including aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material. Each category was then weighed. Sieving and electrostatic separation were not carried out because several components were too large, irregular or composite for the available laboratory equipment.

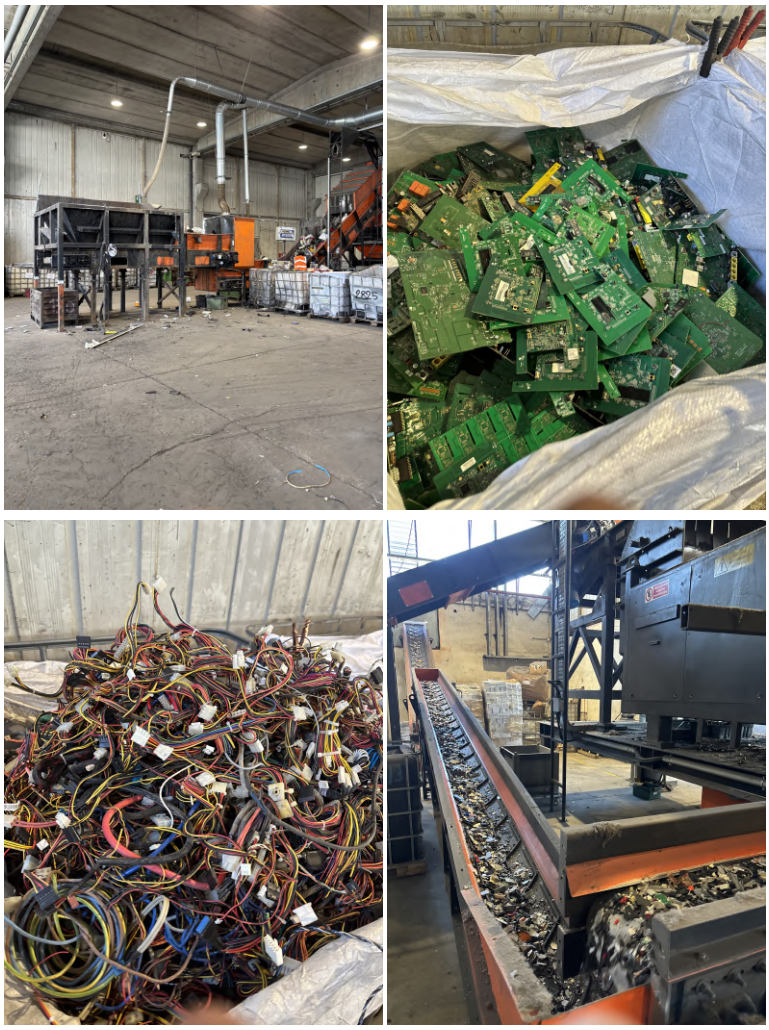


Figure 3.4: Representative views of the small electrical devices stream and its main fractions, including printed circuit boards, wires and conveyor-fed material. *Source: photographs taken by the author during the visit to Transistor S.r.l.*

The visual appearance of this stream confirms its complexity. Unlike the refrigerator-derived Cu/Al fraction, which was mainly composed of metallic particles suitable for further separation tests, the small electrical devices sample contained larger components and mixed items. For this reason, the characterization of this sample was based on manual sorting into broad material categories rather than on particle size classification.

3.6 Material Fractions Selected for Laboratory Work

The two industrial samples were selected because they represented different physical conditions of WEEE-derived materials and could not be examined using the same laboratory procedure.

The refrigerator-derived Cu/Al fraction was used as the main experimental feed. It consisted mainly of aluminium and copper particles, together with a smaller amount of residue. Its particle form made it possible to carry out manual characterization, riffle splitting, electrostatic separation, re-processing and particle-size classification by sieving.

The small electrical devices sample had a different role in the study. It contained larger, irregular and composite components and could not be processed using the available sieving and electrostatic separation equipment. The laboratory work on this sample was therefore limited to manual separation and weighing of the main material categories.



Figure 3.5: Examples of industrial material fractions associated with the samples selected for laboratory characterization and separation tests. *Source: photographs taken by the author during the visit to Transistor S.r.l.*

The experimental route was therefore selected according to the size, shape, composition and processability of each industrial sample.

3.7 Connection Between the Industrial Process and the Laboratory Tests

The laboratory tests were designed to investigate separation issues that were directly connected with the industrial process. In the plant, WEEE treatment produces several output fractions, but these fractions are not always completely pure. Even after mechanical treatment and physical separation, non-ferrous outputs may still contain mixed metals, plastics and other impurities.

The refrigerator-derived copper/aluminium fraction represented a practical example of this situation. Although the material had already passed through industrial processing, copper and aluminium were still present together. The laboratory electrostatic separation tests were therefore used to evaluate whether a dry physical separation process could further improve the quality of this fraction.

The initial electrostatic separation tests on the refrigerator-derived Cu/Al fraction also showed that changing the operating parameters of the separator was not sufficient by itself to obtain a fully satisfactory separation. Although voltage and drum frequency influenced the distribution of copper between the products, the wide particle size distribution and irregular particle shapes of the feed still limited the selectivity of the process.

For this reason, sieving was introduced as a feed-preparation step for the same refrigerator-derived Cu/Al fraction. After particle size classification, the material could be divided into narrower size ranges and selected fine fractions could be tested separately by electrostatic separation. This made it possible to evaluate whether a more homogeneous feed improved copper concentration and recovery.

The small electrical devices sample represented a different problem. In this case, the main difficulty was the high heterogeneity and large size of many components. The sample contained aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material, including wires, capacitors and mixed copper–aluminium pieces. Because many of these components were too large, irregular or unsuitable for the available laboratory size-reduction and sieving equipment, sieving and electrostatic separation were not applied to this sample. The work on this stream was therefore limited to manual characterization and mass determination of the main material categories.

The connection between the industrial process and the laboratory tests can therefore be summarized as follows:

- the industrial plant provided real WEEE output fractions;
- the refrigerator stream was used to study copper/aluminium separation;
- the small electrical devices stream was used to study material heterogeneity through manual characterization and mass determination of its main material

categories;

- electrostatic separation was used to evaluate the possibility of improving metal concentration;
- manual sorting was used when particle size made visual identification more suitable than machine separation.

This approach allowed the experimental work to remain connected with real recycling conditions. The tests were not performed on idealized samples, but on materials generated by an industrial WEEE treatment plant.

3.8 Chapter Summary

This chapter presented the industrial context of the thesis and described the main WEEE streams observed during the plant visit. The refrigerator recycling line was identified as the source of the copper/aluminium-rich fraction used as the main experimental material for the electrostatic separation study. This stream was particularly relevant because aluminium and copper were still present together after industrial treatment, making an additional separation step necessary to improve the quality of the non-ferrous fraction.

The small electrical devices stream represented a different type of WEEE material. It was more heterogeneous and contained printed circuit boards, wires, plastic components, batteries, metallic pieces and mixed residues. Unlike the refrigerator-derived Cu/Al fraction, this sample was not selected for sieving or electrostatic separation in the laboratory work. Instead, it was used for manual characterization in order to quantify its main material categories and to show the complexity of this industrial stream.

The distinction between the two selected samples is central to the experimental work. The refrigerator-derived Cu/Al fraction was suitable for manual characterization, electrostatic separation, re-processing and particle size classification by sieving. The small electrical devices sample, on the other hand, was too coarse, irregular and heterogeneous for the available laboratory sieving and separation equipment, and was therefore characterized only by manual sorting and weighing. This industrial background provides the basis for the experimental methods described in the next chapter.

Chapter 4

Materials and Methods

4.1 Introduction

This chapter describes the experimental methodology adopted for the characterization and treatment of the selected WEEE-derived samples. The laboratory work was designed to connect the industrial observations with measurable separation performance indicators, such as copper purity, copper recovery and mass balance.

Two industrial samples were considered, but they had different roles in the experimental work. The refrigerator-derived Cu/Al fraction represented the main material for the electrostatic separation study. This sample was manually characterized, prepared by riffle splitting, tested under different electrostatic separator operating conditions, re-processed in one selected case, and later classified by particle size through sieving.

The small electrical devices sample was treated differently. This material was more heterogeneous and contained larger components, including aluminium pieces, copper pieces, printed circuit boards, plastics, batteries and mixed/residue material. Due to its size, irregular shape and complexity, this sample was not processed by sieving or electrostatic separation using the available laboratory equipment. It was instead manually characterized by separating and weighing the main material categories.

The methodology therefore combined two complementary approaches: separation testing and particle size classification for the refrigerator-derived Cu/Al fraction, and manual material characterization for the small electrical devices sample.

4.2 Origin and Selection of the Samples

The samples used in the laboratory work were selected from material streams observed during the industrial plant visit. The first sample was related to the

refrigerator recycling line and consisted mainly of aluminium and copper particles. This fraction was selected because copper and aluminium were still present together after industrial treatment, making it suitable for evaluating an additional dry separation step.

The second sample was obtained from the small electrical devices stream. This sample was selected to represent a more heterogeneous WEEE fraction, containing both metallic and non-metallic components. Its role in the experimental work was not to test electrostatic separation, but to quantify the main material categories by manual characterization.

Table 4.1: Samples considered in the laboratory work.

Sample	**Industrial origin**	**Laboratory role and treatment**
Refrigerator-derived Cu/Al fraction	Refrigerator recycling line	Main experimental stream for electrostatic separation. The material was manually characterized, prepared by riffle splitting, tested under different separator conditions, re-processed in one selected case, and later classified by sieving. Selected fine size fractions were also tested separately.
Small electrical devices sample	Small electrical devices stream	Complementary stream for manual material characterization. The sample was separated and weighed into aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material only. No sieving or electrostatic separation was applied to this sample.

4.3 Manual Characterization of the Refrigerator-Derived Cu/Al Fraction

4.3.1 Sorting Procedure

The initial refrigerator-derived non-ferrous sample was manually characterized before machine testing. The material was spread on a working surface and visually separated into three categories:

- aluminium particles;
- copper particles;
- waste and impurities.

Manual sorting was carried out because the sample contained a limited number of material types and because visual identification of aluminium and copper was

possible for most particles. Aluminium particles were generally identified by their light metallic appearance, while copper particles were identified by their reddish metallic colour. Waste and impurities included non-target materials such as plastics, white residues, golden-coloured fragments and other non-metallic or mixed particles.

After sorting, each fraction was weighed separately using a laboratory balance. The initial sample mass was approximately 3032 g. The manually separated fractions were then used to determine the mass distribution of aluminium, copper and waste in the original material.

Table 4.2: Initial manual characterization of the refrigerator-derived Cu/Al fraction.

Fraction	**Mass (g)**	**Mass (%)**	**Min size (mm)**	**Max size (mm)**
Aluminium	2747.90	90.63	2.70	56.86
Copper	205.80	6.79	1.21	63.23
Waste/impurities	60.56	2.00	2.02	55.61
Mass loss	17.74	0.59	–	–
Total initial mass	**3032.00**	**100.00**	–	–

The mass loss was calculated as the difference between the initial total mass and the measured subtotal after manual sorting. This loss may be related to very small particles, dust, material remaining on the working surface or uncertainty during handling.

4.3.2 Particle Size Measurement

The particle size of the refrigerator-derived sample was estimated by measuring the longest dimension of representative particles. This approach was adopted because the particles were irregular in shape and did not have a uniform geometry. For each manually sorted material category, approximate minimum and maximum particle dimensions were recorded.

The measurements showed that the sample had a broad particle size distribution. Aluminium particles ranged approximately from 2.70 mm to 56.86 mm, copper particles from 1.21 mm to 63.23 mm, and waste particles from 2.02 mm to 55.61 mm. This information was important because particle size and shape can influence particle trajectory during electrostatic separation.

4.4 Riffle splitting and Preparation of the Machine Feed

4.4.1 Purpose of riffle splitting

The original refrigerator-derived sample was too large to be used directly in each laboratory separation test. Therefore, a representative smaller feed was prepared using a riffle splitter. riffle splitting was used to reduce the sample mass while maintaining a composition as representative as possible of the original material. Figure 4.1 shows the laboratory riffle splitter adopted in this work. The material



Figure 4.1: Laboratory riffle splitter used to obtain representative subsamples of the refrigerator-derived Cu/Al material prior to electrostatic separation. *Source: photograph taken by the author during the laboratory work.*

was repeatedly divided into smaller portions until the desired sample mass for the following experimental steps was obtained. Before splitting, the material was mixed to reduce the effect of segregation. The sample was then passed through the riffle splitter in several steps until a smaller test feed was obtained. The final feed used for the main machine tests had a mass of approximately 355 g.

4.4.2 Characterization of the Machine-Test Feed

After riffle splitting, the selected feed was manually characterized again. The feed contained 310.70 g of aluminium, 33.80 g of copper and 10.50 g of waste or impurities.

Table 4.3: Composition of the refrigerator-derived feed prepared for electrostatic separation tests.

Fraction	**Mass (g)**	**Mass (%)**
Aluminium	310.70	87.52
Copper	33.80	9.52
Waste/impurities	10.50	2.96
Total	**355.00**	**100.00**

This feed composition was used as the reference for evaluating the separation products. Since copper represented less than 10% of the feed mass, the separation objective was to concentrate copper into a smaller product fraction while reducing the aluminium content in that product.

4.5 Electrostatic Separation of the Refrigerator-Derived Cu/Al Fraction

4.5.1 General Principle of the Test

The refrigerator-derived Cu/Al feed was processed using a laboratory electrostatic separator. The separator was used to exploit differences in the electrical and physical behaviour of particles when exposed to the electric field and rotating drum. The output was collected in separate bins according to the particle trajectories.

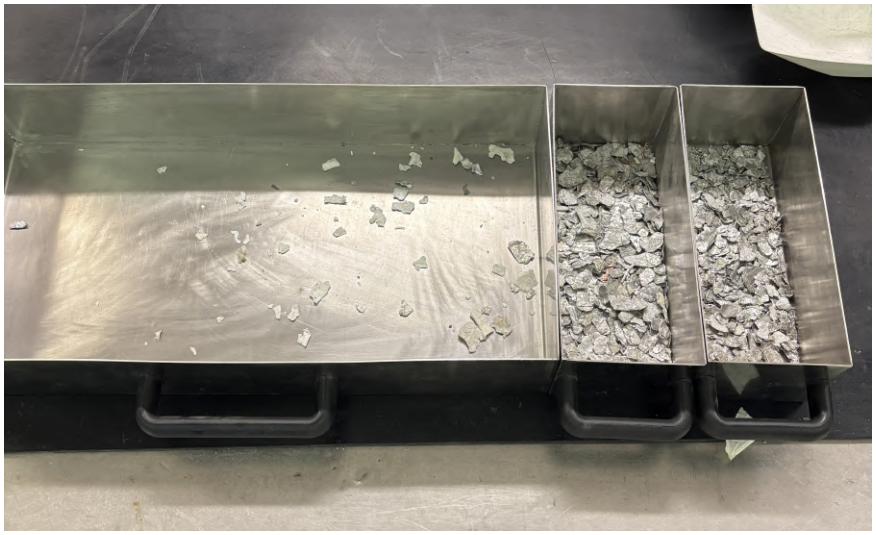


Figure 4.2: Collection bins of the laboratory electrostatic separator after processing the refrigerator-derived Cu/Al fraction. *Source: photograph taken by the author during the laboratory work.*

The separated products collected in the output bins were then weighed and manually re-sorted into aluminium, copper and waste in order to calculate copper purity, copper recovery and mass balance. After each test, the material collected in each bin was weighed. Then, each bin was manually re-sorted into aluminium, copper and waste. This step was necessary because the machine products were not pure fractions, and the composition of each output bin had to be measured directly.

The same general procedure was applied to each machine test:

1. The feed was weighed before the test.
2. The machine operating parameters were set.
3. The feed was introduced at a controlled feeder setting.
4. Output bins were collected separately.
5. Each bin was weighed.
6. Each bin was manually sorted into aluminium, copper and waste.
7. The separated materials from each bin were weighed.
8. Copper purity, copper recovery and mass balance were calculated.

4.5.2 Operating Conditions

Several operating conditions were tested in order to evaluate the effect of voltage and drum frequency on the separation behaviour. The feeder setting was kept at 10% during the recorded tests.

The first test was qualitative and was used mainly to observe the general behaviour of the material. The subsequent tests were quantified by measuring the composition of each output bin. A re-processing test was also performed on Bin 1 from the selected 60 Hz test, because this fraction still contained recoverable copper. Finally, an additional test at 70 Hz was carried out to evaluate the behaviour at a higher drum frequency.



Figure 4.3: Control panel of the laboratory electrostatic separator used to adjust the high-voltage system, drum frequency and vibrating feeder during the tests. *Source: photograph taken by the author during the laboratory work.*

The control panel allowed the main operating parameters of the separator to be adjusted before each test, including the applied voltage, drum frequency and vibrating feeder setting.

Table 4.4: Electrostatic separation tests performed on the refrigerator-derived Cu/Al fraction.

Test	kV	Hz	Feeder (%)	Purpose
Test 1	27	40	10	Qualitative preliminary test
Test 2	30	40	10	Quantitative test
Test 3	30	60	10	Main optimized test
Re-processing	30	60	10	Second pass of Bin 1
Test 4	30	70	10	Higher frequency test

4.5.3 Re-Processing of Bin 1

After the 60 Hz test, Bin 1 still contained a measurable amount of copper. For this reason, this fraction was not discarded. Instead, it was selected for a second pass through the separator. The purpose of this re-processing step was to recover additional copper from an intermediate aluminium-rich fraction without re-mixing all machine products.

Before re-processing, the mass and composition of the Bin 1 fraction were recorded. The re-processing feed had a mass of approximately 259 g and consisted mainly of aluminium, with a measurable copper content. The output products from the second pass were again collected, weighed and manually sorted into aluminium and copper.

This step was important because one-pass separation did not completely separate copper and aluminium. Re-processing was therefore used as a simple multi-stage strategy to improve copper recovery from the intermediate product.

4.6 Sieving of the Refrigerator-Derived Cu/Al Fraction

4.6.1 Reason for Sieving

After the initial electrostatic separation tests, it became clear that changing the operating parameters of the separator alone was not sufficient to obtain a fully satisfactory separation. Although the tests showed differences between the selected frequencies, the feed still contained particles with a wide range of sizes and shapes. This affected the stability of the particle trajectories and limited the selectivity of the separation.

For this reason, sieving was introduced as a feed-preparation step for the refrigerator-derived Cu/Al fraction. The objective was to divide the material into

narrower size ranges and to evaluate whether a more homogeneous feed could improve copper concentration and recovery during electrostatic separation.

4.6.2 Sieving Procedure



Figure 4.4: Particle-size fractions obtained after sieving the refrigerator-derived Cu/Al material. *Source: photograph taken by the author during the laboratory work.*

The refrigerator-derived Cu/Al material selected for the sieving step was divided into different particle size classes using laboratory sieves. Each size fraction was collected separately and weighed. The fine fractions below 10 mm were selected for electrostatic separation tests, while the coarser fractions were characterized by

manual sorting.

Table 4.5: Particle size classification of the refrigerator-derived Cu/Al fraction.

Size fraction	Mass (g)	Mass (%)
< 6.3 mm	371.60	12.44
6.3–8 mm	411.40	13.78
8–10 mm	568.60	19.04
10–12.5 mm	969.60	32.47
12.5–14 mm	296.40	9.93
14–16 mm	213.54	7.15
16–20 mm	137.27	4.60
> 20 mm	17.91	0.60
Total	2986.32	100.00



Figure 4.5: Labelled products collected after sieving, electrostatic separation and manual sorting of the refrigerator-derived Cu/Al material. *Source: photograph taken by the author during the laboratory work.*

4.6.3 Electrostatic Separation of Fine Size Fractions

The three fine size fractions below 10 mm were processed separately using the laboratory electrostatic separator. The same operating condition was used for these

tests in order to focus on the effect of particle size: 30 kV, 60 Hz and 10% feeder. Each size fraction was fed independently to avoid mixing particles with different size ranges.

For each test, the feed mass was recorded. The output bins were then collected separately, weighed and manually sorted into aluminium, copper and waste. Copper purity and copper recovery were calculated for the copper-rich product bin.

Table 4.6: Conditions used for electrostatic separation of fine Cu/Al size fractions.

Size fraction	Feed mass (g)	kV	Hz	Feeder (%)
< 6.3 mm	371.60	30	60	10
6.3–8 mm	411.40	30	60	10
8–10 mm	568.60	30	60	10

The objective of these tests was to evaluate whether particle size classification could improve the quality of the copper-rich product compared with the initial tests performed on the unsieved Cu/Al fraction.

4.6.4 Manual Sorting of Coarser Size Fractions

Fractions larger than 10 mm were not processed in the electrostatic separator. Instead, they were manually sorted into aluminium, copper and waste. This decision was based on the larger particle size, which made visual identification more reliable and allowed direct manual characterization of the coarse material.

Table 4.7: Manual sorting plan for coarse Cu/Al size fractions.

Size fraction	Initial mass (g)	Sorting categories
10–12.5 mm	969.60	Al, Cu, waste
12.5–14 mm	296.40	Al, Cu, waste
14–16 mm	213.54	Al, Cu, waste
16–20 mm	137.27	Al, Cu, waste
> 20 mm	17.91	Al, Cu, waste

This step provided information on the composition of the coarser part of the refrigerator-derived Cu/Al fraction without applying machine separation.

4.7 Manual Characterization of the Small Electrical Devices Sample

The small electrical devices sample was manually characterized because it was not suitable for laboratory sieving or electrostatic separation. The sample contained large, irregular and heterogeneous components, including metallic pieces, printed circuit boards, wires, plastics, batteries and mixed electronic residues. Several components were too large or too complex to be processed with the available laboratory size-reduction and sieving equipment.

The characterization was therefore based on manual separation into broad material categories. Each category was collected and weighed separately. The mixed/residue fraction included items that could not be reliably assigned to a single material category by simple manual sorting, such as capacitors, wires, mixed copper– aluminium pieces and small heterogeneous components.



Figure 4.6: Manual characterization of the small electrical devices sample into its main material categories. *Source: photograph taken by the author during the laboratory work.*

This visual classification supports the mass-based characterization of the sample and shows the heterogeneous nature of the small electrical devices stream.

Table 4.8: Manual characterization categories for the small electrical devices sample.

Category	Description
Aluminium	Aluminium-rich metallic pieces identified by manual sorting.
Copper	Copper-rich pieces and clearly identifiable copper components.
Printed circuit boards	PCB fragments and electronic boards.
Plastics	Plastic pieces separated as an individual category.
Batteries	Battery components manually identified in the sample.
Mixed/residue	Wires, capacitors, mixed Cu–Al pieces and heterogeneous components that could not be reliably assigned to a single material category by simple manual sorting.

No electrostatic separation indicators, such as copper purity or copper recovery, were calculated for this sample because no machine separation test was performed on it. The results of the manual characterization are presented in Chapter 5.

4.8 Calculation Methods

The experimental results were evaluated using mass-based indicators. The main parameters calculated for the electrostatic separation tests were mass percentage, copper purity, copper recovery and mass balance. These indicators were selected because they allow the comparison of different operating conditions, size fractions and output products using directly measured masses.

For the refrigerator-derived Cu/Al fraction, the calculations were based on the measured masses of aluminium, copper and waste in the feed and in the output bins. For the small electrical devices sample, the calculation was limited to mass percentage of the manually separated material categories, because this sample was not processed by electrostatic separation.

4.8.1 Mass Percentage

The mass percentage of each material fraction was calculated as the ratio between the mass of the selected fraction and the total mass of the corresponding sample, feed or size class:

$$\text{Mass percentage}(\%) = \frac{m_i}{m_{\text{total}}} \times 100 \tag{4.1}$$

where m_i is the mass of the selected material fraction, such as aluminium, copper or waste, and m_{total} is the total mass of the considered sample or size fraction.

This calculation was used during manual characterization, sieving analysis and manual sorting of the coarse fractions. It made it possible to describe the composition of each material stream in terms of relative mass contribution.

4.8.2 Copper Purity

Copper purity was used to evaluate the quality of the copper-rich product obtained after electrostatic separation. For each output bin, copper purity was calculated as:

$$\text{Cu purity}(\%) = \frac{m_{\text{Cu,bin}}}{m_{\text{bin}}} \times 100 \tag{4.2}$$

where $m_{\text{Cu,bin}}$ is the mass of copper manually recovered from the selected bin, and m_{bin} is the total mass of that bin before manual re-sorting.

This parameter indicates the degree of copper enrichment in a product fraction. A high copper purity means that the selected bin contains a relatively high proportion of copper compared with aluminium and waste. In this work, copper purity was particularly useful for identifying the copper-rich product among the output bins of the electrostatic separator.

4.8.3 Copper Recovery

Copper recovery was calculated to determine the fraction of the total copper contained in the feed that was recovered in a selected output bin. It was calculated as:

$$\text{Cu recovery}(\%) = \frac{m_{\text{Cu,selected bin}}}{m_{\text{Cu,feed}}} \times 100 \tag{4.3}$$

where $m_{\text{Cu,selected bin}}$ is the mass of copper recovered in the selected product bin, and $m_{\text{Cu,feed}}$ is the total mass of copper initially present in the feed.

Copper recovery was used together with copper purity because the two indicators describe different aspects of separation performance. Copper purity describes the quality of the product, while copper recovery describes how much of the available copper was actually collected in that product. For this reason, a separation condition cannot be evaluated only by purity or only by recovery; both values must be considered together.

4.8.4 Mass Balance and Mass Loss

For each separation test, a mass balance was calculated by comparing the initial feed mass with the total mass of the collected output bins. The absolute mass loss was calculated as:

$$m_{\text{loss}} = m_{\text{feed}} - \sum_{j=1}^{n} m_{\text{output},j} \tag{4.4}$$

where m_{feed} is the mass introduced into the separator, $m_{\text{output},j}$ is the mass collected in output bin j, and n is the total number of output bins.

The percentage mass loss was calculated as:

$$\text{Mass loss}(\%) = \frac{m_{\text{feed}} - \sum_{j=1}^{n} m_{\text{output},j}}{m_{\text{feed}}} \times 100 \tag{4.5}$$

Mass loss was used as a quality control parameter. A small loss may be caused by fine particles remaining in the machine, dust formation, particles lost during transfer, material retained on the working surface or weighing uncertainty. In this work, mass balance was checked after each test in order to evaluate the reliability of the collected data.

4.8.5 Interpretation of the Indicators

The calculated indicators were used to compare both operating conditions and particle size fractions. For the refrigerator-derived Cu/Al fraction, copper purity and recovery were used to compare the effect of voltage and drum frequency on the electrostatic separation performance. The same indicators were also used for the sieved fine Cu/Al size fractions tested separately in the electrostatic separator. For the small electrical devices sample, only mass percentage was calculated, because no electrostatic separation test was performed on this stream.

In general, a useful separation condition should produce a copper-rich product with both acceptable copper purity and acceptable copper recovery. A very pure product with very low recovery may not be practically useful, because most of the copper remains in other fractions. Similarly, a product with high recovery but low purity may still contain too much aluminium or waste. Therefore, the discussion of the results was based on the combined interpretation of product mass, copper purity, copper recovery and mass balance.

4.9 Data Recording and Quality Control

All masses were recorded in grams. The main data recorded for each test were:

- feed mass;
- machine settings;
- total mass collected in each bin;

- aluminium mass in each bin;
- copper mass in each bin;
- waste mass in each bin;
- calculated copper purity;
- calculated copper recovery;
- mass balance and mass loss.

Output products were kept separated and labelled after each test. This was particularly important for the re-processing test, because Bin 1 from the selected 60 Hz experiment was used as the feed for an additional separation step.

The main sources of uncertainty in the methodology were manual sorting errors, weighing uncertainty, particle losses during handling, possible retention of fine particles inside the separator and the irregular shape of the particles. In addition, environmental conditions such as moisture and humidity may affect electrostatic separation performance. These conditions were not systematically recorded during all tests and should be considered as a limitation of the experimental work.

4.10 Summary of the Experimental Methodology

The methodology adopted in this work combined industrial sample selection, manual characterization, sample splitting, electrostatic separation, re-processing and particle size classification. The refrigerator-derived Cu/Al fraction was used as the main experimental material for evaluating copper concentration by electrostatic separation. This sample was first characterized manually, then processed under different operating conditions, re-processed in one selected case, and finally classified by particle size through sieving.

The sieving step was introduced after the initial electrostatic separation tests, because the results showed that machine settings alone were not sufficient to fully optimize the separation. By dividing the refrigerator-derived Cu/Al fraction into narrower size ranges, it became possible to evaluate the role of particle size as a key factor affecting copper purity and copper recovery.

The small electrical devices sample was treated differently. Due to its large component size, irregular shape and high heterogeneity, this sample was not processed by sieving or electrostatic separation with the available laboratory equipment. It was manually characterized into aluminium, copper, printed circuit boards, plastics, batteries and mixed/residue material.

The overall experimental sequence can be summarized as follows:

1. Selection of real WEEE-derived samples from the industrial context.
2. Manual characterization of the refrigerator-derived Cu/Al fraction.
3. Measurement of approximate particle size range for the refrigerator-derived Cu/Al fraction.
4. riffle splitting to obtain a representative machine-test feed.
5. Electrostatic separation of the refrigerator-derived Cu/Al fraction under different operating conditions.
6. Re-processing of an intermediate output fraction containing residual copper.
7. Sieving of the refrigerator-derived Cu/Al fraction into particle size classes.
8. Electrostatic separation of selected fine size fractions below 10 mm.
9. Manual sorting of the coarser size fractions of the refrigerator-derived Cu/Al fraction.
10. Manual characterization of the small electrical devices sample into material categories.
11. Calculation of mass percentage, copper purity, copper recovery and mass balance where applicable.

This methodology provided the basis for interpreting the influence of machine settings, re-processing and particle size classification on the recovery of copper from the refrigerator-derived Cu/Al fraction, while also documenting the material complexity of the small electrical devices stream.

Chapter 5

Results and Discussion

5.1 Introduction

This chapter presents and discusses the experimental results obtained from the characterization and treatment of the selected WEEE-derived samples. The results are organized according to the role of each material stream in the experimental work.

The first and main part of the chapter concerns the refrigerator-derived Cu/Al fraction. For this material, the discussion includes the initial manual characterization, the preparation of the machine-test feed by riffle splitting, the effect of electrostatic separator operating conditions, and the re-processing of an intermediate output fraction.

The second part of the chapter focuses on particle size classification of the same refrigerator-derived Cu/Al fraction. After the initial electrostatic separation tests, sieving was introduced as a feed-preparation step because the unsieved material contained particles with a wide range of sizes and shapes. The fine size fractions were then tested separately by electrostatic separation, while the coarser fractions were manually sorted.

The final experimental part of the chapter presents the manual characterization of the small electrical devices sample. This sample was not processed by sieving or electrostatic separation because it contained large, irregular and heterogeneous components that were not suitable for the available laboratory equipment.The two industrial streams are then compared in terms of their material characteristics and suitability for the investigated treatment approaches. Finally, a preliminary economic and valorization assessment is presented, including market-value benchmarks, an annualized R1 throughput scenario, additional treatment costs, and a comparison between the reference and proposed upgrading strategies.

The main indicators used to evaluate the separation results were copper purity,

copper recovery and mass balance. These indicators were used for the refrigerator-derived Cu/Al fraction and for the sieved fine Cu/Al size fractions. For the small electrical devices sample, only mass percentage was calculated because no machine separation test was performed on this material.

5.2 Characterization of the Refrigerator-Derived Cu/Al Fraction

5.2.1 Initial Material Composition

The refrigerator-derived sample was first manually sorted into aluminium, copper and waste/impurity fractions. The initial total mass of the sample was 3032.00 g. The results showed that the sample was strongly aluminium-dominant, while copper represented a smaller but valuable fraction.

Table 5.1: Initial composition of the refrigerator-derived Cu/Al fraction.

Fraction	**Mass (g)**	**Mass (%)**	**Min size (mm)**	**Max size (mm)**
Aluminium	2747.90	90.63	2.70	56.86
Copper	205.80	6.79	1.21	63.23
Waste/impurities	60.56	2.00	2.02	55.61
Mass loss	17.74	0.59	–	–
Total initial mass	**3032.00**	**100.00**	–	–

The sample contained approximately 90.63% aluminium and 6.79% copper. This confirmed that the material was not a balanced Cu/Al mixture, but an aluminium-rich non-ferrous fraction containing a smaller copper content. From a recovery point of view, this is important because the target metal was present at relatively low concentration compared with aluminium.

The particle size range was also broad. Aluminium particles ranged from 2.70 mm to 56.86 mm, while copper particles ranged from 1.21 mm to 63.23 mm. This wide range suggested that particle trajectory during electrostatic separation could be affected not only by material conductivity, but also by particle size, shape and mass.

5.2.2 Machine-Test Feed after riffle splitting

After riffle splitting, a representative machine-test feed of approximately 355.00 g was prepared. The feed contained 310.70 g of aluminium, 33.80 g of copper and 10.50 g of waste or impurities.

Table 5.2: Composition of the feed used for electrostatic separation tests.

Fraction	**Mass (g)**	**Mass (%)**
Aluminium	310.70	87.52
Copper	33.80	9.52
Waste/impurities	10.50	2.96
Total	**355.00**	**100.00**

The feed composition was similar to the original sample, although the copper percentage in the test feed was slightly higher than in the initial bulk sample. This difference can be considered acceptable because riffle splitting reduces the sample mass but cannot completely eliminate variability in a heterogeneous material. The feed was still clearly aluminium-rich, and the main objective of the electrostatic tests was therefore to concentrate copper into a smaller output fraction.

5.3 Electrostatic Separation of the Refrigerator-Derived Fraction

5.3.1 Preliminary Qualitative Test

The first electrostatic test was carried out at 27 kV, 40 Hz and 10% feeder. This test was qualitative and was mainly used to observe the general behaviour of the material in the separator. The separation was not satisfactory, and a complete quantitative mass balance was not recorded.

The preliminary test was useful because it showed that the initial machine setting was not sufficient to produce a clearly copper-rich fraction. It also indicated that the material response was influenced by particle trajectory and by the distribution of particles among the collection bins. For this reason, the following tests were performed at 30 kV and different drum frequencies.

5.3.2 Comparison of the Main Electrostatic Tests

Three quantitative tests were compared for the refrigerator-derived fraction: 30 kV and 40 Hz, 30 kV and 60 Hz, and 30 kV and 70 Hz. The feeder setting was kept at 10% in all tests. The main comparison was based on the copper-rich output bin, which was Bin 2 in the recorded tests.

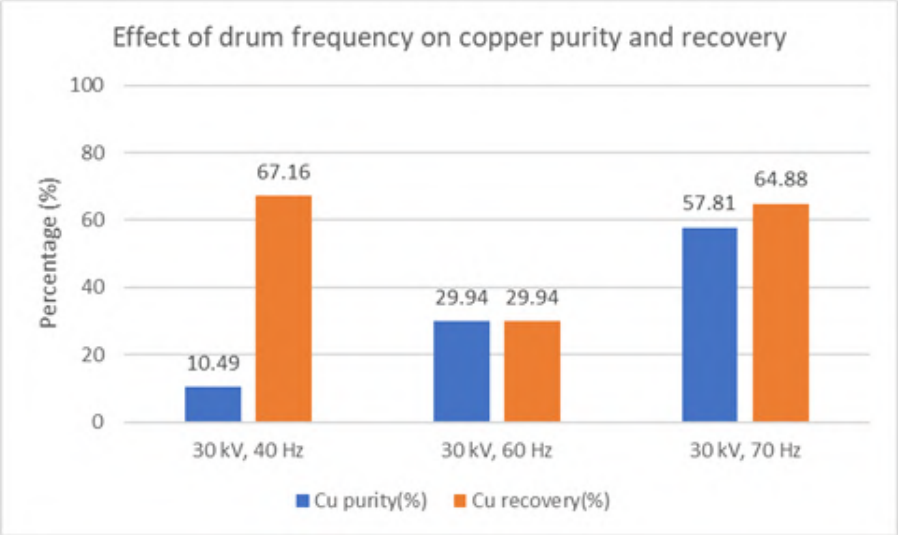


Figure 5.1: Comparison of copper purity and copper recovery obtained for the copper-rich product under different drum frequencies. *Source: author's elaboration based on the experimental data obtained in this study.*

Figure 5.1 shows that increasing the drum frequency improved copper purity, while the best compromise between copper purity and copper recovery was obtained at 60 Hz.

Table 5.3: Performance of the copper-rich product under different electrostatic separation conditions.

Condition	Bin 2 mass (g)	Cu in Bin 2 (g)	Cu purity (%)	Cu recovery (%)	Mass loss (%)
30 kV, 40 Hz	214.50	22.50	10.49	67.16	0.04
30 kV, 60 Hz	80.27	24.03	29.94	71.48	0.13
30 kV, 70 Hz	37.71	21.80	57.81	64.88	0.30

At 30 kV and 40 Hz, Bin 2 collected a relatively large mass of material, 214.50 g, but its copper purity was only 10.49%. This means that the product was only slightly enriched in copper compared with the feed and was still dominated by aluminium. Although the copper recovery was 67.16%, the low purity shows that the separation was not selective enough.

At 30 kV and 60 Hz, the behaviour improved significantly. The mass of Bin 2 decreased to 80.27 g, but the copper mass in this bin increased slightly to 24.03 g. As a result, copper purity increased to 29.94%, while copper recovery also increased to 71.48%. This indicates that the 60 Hz condition produced a smaller but more concentrated copper-rich product.

At 30 kV and 70 Hz, the copper-rich product became even smaller, with a Bin 2

mass of 37.71 g. However, the copper purity increased strongly to 57.81%, which was the highest purity obtained among the tested one-pass conditions. The copper recovery decreased to 64.88%, meaning that the product was purer but collected a smaller fraction of the total copper.

These results show a clear trade-off between copper purity and copper recovery. The 60 Hz condition provided the best compromise between copper concentration and copper recovery, while the 70 Hz condition produced the highest copper purity but with lower recovery. The 40 Hz condition was less effective because it produced a large mixed product with limited copper enrichment.

5.3.3 Distribution of Copper among the Output Bins

The distribution of copper among the bins gives additional information about the separation behaviour. In the 40 Hz test, copper was distributed mainly between Bin 1 and Bin 2. Bin 1 contained 11.00 g of copper, while Bin 2 contained 22.50 g. Since Bin 2 was still aluminium-rich, this test did not produce a clean separation.

In the 60 Hz test, Bin 2 collected 24.03 g of copper, while Bin 1 still contained 9.59 g. This shows that the 60 Hz condition concentrated copper better than the 40 Hz condition, but it did not recover all copper into the copper-rich bin. The presence of copper in Bin 1 was the reason for selecting this output fraction for re-processing.

In the 70 Hz test, Bin 2 had the highest copper purity, but Bin 1 still contained 11.80 g of copper. This indicates that increasing the frequency to 70 Hz improved the selectivity of Bin 2, but it also caused part of the copper to remain in the aluminium-rich product. Therefore, the 70 Hz condition may be useful when a higher grade copper-rich product is preferred, but it may require an additional recovery step to reduce copper losses in Bin 1.

5.4 Re-Processing of Bin 1 from the 60 Hz Test

5.4.1 Purpose of Re-Processing

After the 60 Hz test, Bin 1 was selected for re-processing because it still contained a measurable amount of copper. The objective was to evaluate whether a second pass through the electrostatic separator could recover additional copper from an intermediate aluminium-rich fraction.

The re-processed feed had a total mass of 258.63 g and contained 248.30 g of aluminium and 10.66 g of copper. This feed was highly aluminium-rich, but the copper content was still relevant enough to justify a second separation step.

Table 5.4: Results of re-processing Bin 1 from the 60 Hz test.

Output	Total mass (g)	Al (g)	Cu (g)	Cu purity (%)
Bin 1	243.00	239.00	3.74	1.54
Bin 2	15.72	9.22	6.65	42.30
Total output	**258.72**	**248.22**	**10.39**	**4.02**

The re-processing test produced a small Bin 2 fraction with 42.30% copper purity. This value was much higher than the copper concentration in the re-processing feed. The mass of Bin 2 was only 15.72 g, but it contained 6.65 g of copper, corresponding to about 62% of the copper measured in the re-processed feed balance. Small differences between the feed balance and the total output balance were attributed to manual handling and weighing uncertainty.

This result confirms that re-processing can be useful when an intermediate product still contains recoverable copper. The re-processing step did not produce a pure copper product, but it improved the concentration of copper in a smaller fraction and reduced copper loss in the aluminium-rich product.

The result also supports the idea that one-pass electrostatic separation may not be sufficient for real WEEE-derived Cu/Al fractions. A multi-stage approach can improve the recovery of valuable metal from intermediate outputs, especially when copper remains distributed between bins after the first separation.

5.5 Discussion of the Refrigerator-Derived Cu/Al Tests

The electrostatic separation tests showed that operating conditions strongly affected the distribution of copper and aluminium among the bins. Increasing the frequency from 40 Hz to 60 Hz improved both copper purity and copper recovery in Bin 2. Increasing the frequency further to 70 Hz produced the highest copper purity, but with lower recovery.

This behaviour suggests that particle trajectory became more selective at higher frequency, but also that some copper particles continued to report to the aluminium-rich bin. The separation was therefore not controlled only by the conductivity of the particles. Particle size, particle shape, mass, surface condition and the position of the collecting bins likely contributed to the final distribution.

The 60 Hz condition can be considered the best compromise among the one-pass tests because it produced a copper-rich product with 29.94% copper purity and 71.48% copper recovery. The 70 Hz condition can be considered the best condition in terms of purity, because it produced a Bin 2 product with 57.81% copper.

However, the lower recovery indicates that this condition should be combined with re-processing if the objective is to minimize copper losses.

Overall, the results show that the refrigerator-derived fraction can be upgraded by electrostatic separation, but complete Cu/Al separation was not achieved in one step. The process should therefore be interpreted as an upgrading operation rather than a final purification process.

5.6 Particle-Size Classification of the Cu/Al Fraction

After the initial electrostatic separation tests on the refrigerator-derived Cu/Al fraction, it became clear that changing the operating parameters of the separator alone was not sufficient to obtain a fully satisfactory separation. The material contained particles with different sizes and shapes, and this wide particle size distribution affected the stability and selectivity of the process.

For this reason, sieving was introduced as a feed-preparation step for the same refrigerator-derived Cu/Al fraction. The objective was to divide the material into narrower size ranges and to evaluate whether a more homogeneous feed could improve the separation performance. The particle size distribution obtained after sieving is reported in Table 5.5.

Table 5.5: Particle size classification of the refrigerator-derived Cu/Al fraction.

Size fraction	**Mass (g)**	**Mass (%)**
< 6.3 mm	371.60	12.44
6.3–8 mm	411.40	13.78
8–10 mm	568.60	19.04
10–12.5 mm	969.60	32.47
12.5–14 mm	296.40	9.93
14–16 mm	213.54	7.15
16–20 mm	137.27	4.60
> 20 mm	17.91	0.60
Total	2986.32	100.00

The results show that the largest size fraction was 10–12.5 mm, representing 32.47% of the total sieved material. The three fine fractions below 10 mm together represented 45.26% of the total mass. These fine fractions were selected for electrostatic separation tests because their smaller particle size made them more suitable for controlled laboratory processing.

The introduction of sieving therefore changed the experimental approach. Instead of processing a broad and heterogeneous Cu/Al feed in a single test, the material was divided into narrower size classes. This made it possible to investigate the effect of particle size on copper purity and copper recovery more clearly.

5.7 Electrostatic Separation of the Sieved Fine Cu/Al Fractions

The three fine size fractions below 10 mm were processed separately using the laboratory electrostatic separator. The same operating condition was used for all three tests: 30 kV, 60 Hz and 10% feeder. This condition was selected because the previous tests on the unsieved Cu/Al fraction showed that 60 Hz provided the best compromise between copper purity and copper recovery.

The copper-rich product was collected in Bin 2. The mass of Bin 2, the amount of copper contained in Bin 2, copper purity and copper recovery are reported in Table 5.6.

Table 5.6: Copper-rich product obtained from electrostatic separation of fine Cu/Al size fractions.

Size fraction	Bin 2 mass (g)	Cu in Bin 2 (g)	Cu purity (%)	Cu recovery (%)
< 6.3 mm	77.80	58.44	75.12	74.29
6.3–8 mm	34.84	20.22	58.04	71.12
8–10 mm	59.67	31.88	53.43	69.17

The finest fraction, smaller than 6.3 mm, produced the best copper-rich product, with a copper purity of 75.12% and a copper recovery of 74.29%. This result was significantly better than the best purity obtained during the initial tests performed on the unsieved Cu/Al fraction. The 6.3–8 mm and 8–10 mm fractions also produced copper-rich products, but with lower copper purities of 58.04% and 53.43%, respectively.

These results confirm that particle size classification played a key role in improving the electrostatic separation performance. By reducing the variability of particle size within each test, the behaviour of the material became more controlled and the copper-rich product became more concentrated. This shows that sieving was not only a descriptive characterization step, but an essential pre-treatment operation for improving the separation of the refrigerator-derived Cu/Al fraction.

5.8 Manual Sorting of the Coarse Cu/Al Size Fractions

The size fractions larger than 10 mm were not processed by electrostatic separation. Instead, they were manually sorted into aluminium, copper and waste. This approach was selected because the larger particles were easier to identify visually, while their size and shape made them less suitable for the same laboratory electrostatic separation conditions used for the fine fractions.

The manual sorting results for the coarse size fractions are reported in Table 5.7.

Table 5.7: Manual sorting results for the coarse Cu/Al size fractions.

Size fraction	**Initial mass (g)**	**Al (g)**	**Cu (g)**	**Waste (g)**	**Loss (g)**
10–12.5 mm	969.60	907.80	51.03	10.62	0.15
12.5–14 mm	296.40	277.00	15.00	4.35	0.05
14–16 mm	213.54	204.03	5.39	4.06	0.06
16–20 mm	137.27	135.17	0.00	2.09	0.01
$>$ 20 mm	17.91	17.17	0.00	0.71	0.03
Total	1634.72	1541.17	71.42	21.83	0.30

The coarse fractions were mainly composed of aluminium. The total aluminium mass in the coarse fractions was 1541.17 g, corresponding to the dominant material in this part of the sample. Copper was mostly concentrated in the 10–12.5 mm and 12.5–14 mm fractions, while no copper was identified in the 16–20 mm and $>$ 20 mm fractions.

The results of the coarse manual sorting support the importance of particle size classification. Fine fractions were more suitable for electrostatic separation, while coarser fractions could be characterized reliably by manual sorting. This combined approach made it possible to obtain a more complete understanding of the refrigerator-derived Cu/Al fraction.

5.9 Manual Characterization of the Small Electrical Devices Sample

The small electrical devices sample was characterized manually because it was not suitable for sieving or electrostatic separation using the available laboratory equipment. Unlike the refrigerator-derived Cu/Al fraction, this sample was not mainly composed of liberated metallic particles. It contained larger and more heterogeneous components, including aluminium pieces, copper pieces, printed circuit boards, plastics, batteries and mixed electronic residues.

The total mass of the characterized sample was 6297.60 g. The material was manually separated into the main categories reported in Table 5.8. The mixed/residue fraction included components that could not be reliably assigned to a single material category by simple manual sorting, such as wires, capacitors, mixed copper– aluminium pieces and other heterogeneous electronic components.

Table 5.8: Manual characterization of the small electrical devices sample.

Material category	**Mass (g)**	**Mass (%)**
Aluminium	3645.30	57.88
Copper	251.70	4.00
Printed circuit boards	278.50	4.42
Plastics	26.31	0.42
Batteries	35.62	0.57
Mixed/residue	2059.30	32.70
Mass loss	0.87	0.01
Total	6297.60	100.00

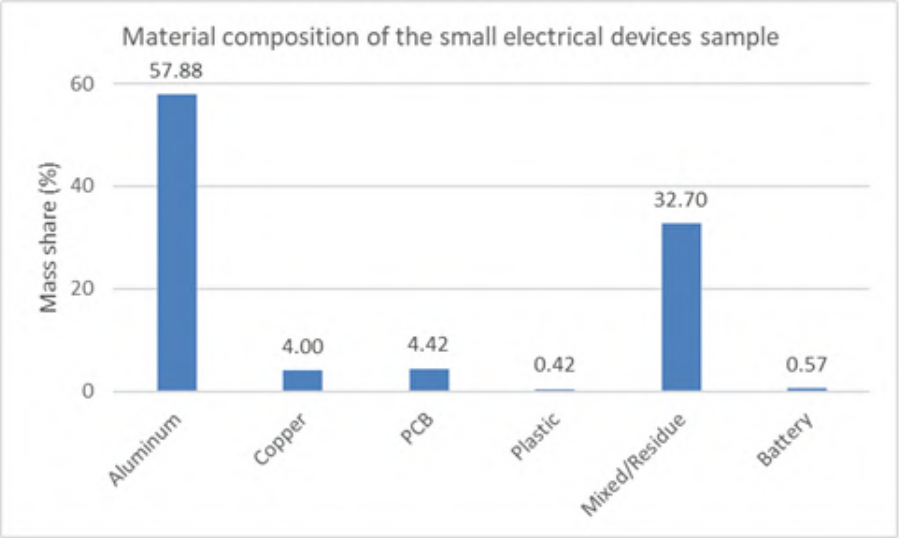


Figure 5.2: Mass composition of the manually characterized small electrical devices sample. *Source: author's elaboration based on the manual characterization data obtained in this study.*

Figure 5.2 shows the mass distribution of the main material categories obtained from the manual characterization of the small electrical devices sample. The result highlights the heterogeneous nature of this stream and confirms that a significant

part of the sample consisted of mixed or composite items that could not be further separated by simple manual sorting. The results show that aluminium was the dominant material category, accounting for 3645.30 g, corresponding to 57.88% of the total sample mass. The copper fraction represented 251.70 g, equal to 4.00% of the total mass, while printed circuit boards accounted for 278.50 g, or 4.42%.

A significant part of the sample was represented by the mixed/residue fraction, which accounted for 2059.30 g, corresponding to 32.70% of the total mass. This high value confirms the heterogeneous nature of the small electrical devices stream. The presence of wires, capacitors, mixed Cu–Al pieces and complex electronic components made this sample less suitable for direct laboratory sieving and electrostatic separation.

Compared with the refrigerator-derived Cu/Al fraction, the small electrical devices sample presented a higher degree of material complexity. The refrigerator-derived Cu/Al fraction was mainly composed of metallic particles and could therefore be processed by electrostatic separation and sieving. In contrast, the small electrical devices sample required manual characterization because many components were too large, irregular or composite to be treated with the available laboratory equipment.

5.10 Comparison of the Two Industrial Samples

The two industrial samples considered in this work had different characteristics and therefore required different laboratory approaches. The refrigerator-derived Cu/Al fraction was mainly composed of aluminium and copper particles. Although the material was not completely liberated and still contained waste or impurities, it was suitable for electrostatic separation tests because the target materials were present as metallic particles.

In contrast, the small electrical devices sample was much more heterogeneous. It contained aluminium, copper, printed circuit boards, plastics, batteries and a large mixed/residue fraction. Many components were large, irregular, composite or difficult to assign to a single material category. For this reason, the sample was not suitable for laboratory sieving or electrostatic separation using the available equipment, and manual characterization was the most appropriate approach.

Table 5.9: Comparison between the two industrial samples considered in this work.

Aspect	**Refrigerator-derived Cu/Al fraction**	**Small electrical devices sample**
Industrial origin	Refrigerator recycling line	Small electrical devices stream
Main material characteristics	Mainly aluminium and copper particles, with limited impurities	Highly heterogeneous mixture of metals, PCBs, plastics, batteries and mixed electronic residues
Main laboratory objective	Copper concentration and evaluation of electrostatic separation performance	Manual characterization of material categories
Suitability for sieving	Suitable for particle size classification	Not suitable with the available laboratory equipment due to large and irregular components
Suitability for electrostatic separation	Suitable, especially after particle size classification	Not processed by electrostatic separation in this work
Main outcome	Particle size classification improved copper purity and helped clarify the separation behaviour	The stream showed high material complexity and a large mixed/residue fraction

The comparison shows that the effectiveness of a separation method depends not only on the selected technology, but also on the physical condition of the feed. The refrigerator-derived Cu/Al fraction could be processed by electrostatic separation because the material was already in particle form and mainly composed of two conductive metals. However, the initial tests showed that operating parameters alone were not sufficient. The introduction of sieving was essential because it reduced the variability of the feed and made the separation behaviour more controlled.

The small electrical devices sample represented a different situation. Its high heterogeneity and large component size limited the possibility of applying the same laboratory procedure. In this case, the most useful result was the quantification of the main material categories, especially the high aluminium content and the large mixed/residue fraction. This confirms that different WEEE streams may require different preparation and treatment strategies.

5.11 Preliminary Economic and Valorization Assessment

5.11.1 Scope of the Economic Assessment

In addition to technical separation performance, the practical application of a WEEE recovery process depends on whether the recovered fractions have sufficient economic value to justify the additional treatment steps required to produce them. Economic performance in WEEE recycling is influenced by several interacting factors, including the composition of the incoming material, the market value of the recovered materials, product purity, recovery rate, processing capacity, labour requirements, energy consumption and disposal costs [17, 18].

The present thesis was not designed as a complete techno-economic assessment. Detailed industrial information on labour costs, electricity consumption of the separator, equipment depreciation, maintenance, industrial-scale throughput and actual sales contracts for the recovered fractions was not available. Therefore, the following analysis should be considered a preliminary screening-level assessment of the economic and valorization potential of the investigated materials rather than a calculation of plant profitability.

The assessment combines three sources of information: the material fractions reported in the Transistor S.r.l. company presentation, the experimental results obtained in this thesis, and reference market prices for copper and aluminium. This approach makes it possible to evaluate whether the separation strategy moves the material in a direction that could be economically favourable, while avoiding unsupported estimates of actual revenues or profits.

5.11.2 Industrial Material Flows and Valuable Fractions

The industrial information provided by Transistor S.r.l. shows that material valorization represents an important part of the WEEE treatment process. The company separates different output fractions, including ferrous and non-ferrous metals, plastics, cables, electronic boards and other components, which can subsequently be directed to appropriate recycling or recovery routes [19, 20].

For the R1 refrigerator treatment line, the company presentation reports aluminium and copper fractions corresponding to approximately 3.31% and 0.21% of the treated material, respectively. Both fractions are reported as being directed predominantly to material recovery. Although their combined mass represents only about 3.52% of the treated R1 stream, their economic relevance is greater than their mass percentage alone may suggest because they are non-ferrous metals with established secondary-material markets.

The R4 stream presents a different valorization profile. In the representative lot

reported in the company presentation, aluminium accounted for 4.37%, copper for 0.13%, brass for 0.33%, shredded electronic boards for 0.28%, and mixed boards for 1.54%. Together, these selected fractions represented approximately 6.65% of the lot mass. Additional potentially valuable fractions, including cables, motors and transformers, were also reported. The economic value of these components cannot be estimated reliably from metal exchange prices alone because their value depends on composition, quality and downstream processing requirements.

The public information provided by Transistor S.r.l. also indicates that the company commercially valorizes several categories of electronic waste and metals, including aluminium, brass, copper, cables, motors, transformers and electronic boards. The final economic value depends on material selection and logistics, and transport costs increase with distance from the treatment facility [21]. This confirms that the economic feasibility of material recovery depends not only on the intrinsic value of the contained metals, but also on the quality and quantity of the fraction and the cost of moving and processing it.

Table 5.10: Selected potentially valuable fractions reported for the R1 and R4 treatment streams in the Transistor S.r.l. company presentation.

Fraction	**R1 (%)**	**R4 lot (%)**
Aluminium	3.31	4.37
Copper	0.21	0.13
Brass	–	0.33
Shredded electronic boards	–	0.28
Mixed electronic boards	–	1.54
Selected total	3.52	6.65

Source: author's elaboration based on data provided in the Transistor S.r.l. company presentation.

5.11.3 Indicative Market Value of the R1 Aluminium and Copper Fractions

A preliminary indication of the economic relevance of the R1 non-ferrous output can be obtained by combining the material fractions reported by the company with reference metal prices. The London Metal Exchange (LME) Official Prices are widely used as reference prices for physical metal contracts. On 28 July 2026, the LME cash ask prices were approximately 13,341 USD/t for copper and 3,105.5 USD/t for aluminium [22]. Using an EUR/USD reference rate of 1.1380 reported by the European Central Bank on 29 July 2026 [23], these values correspond approximately to 11,723 EUR/t for copper and 2,729 EUR/t for aluminium.

These prices must not be interpreted as the actual selling prices of the recycled

fractions produced by the plant. LME quotations refer to standardized market metals, whereas WEEE-derived products may contain impurities and may be subject to discounts, treatment charges, transport costs and contractual specifications. They are therefore used here only as reference benchmarks for comparing the relative economic importance of the recovered metals.

Table 5.11: Indicative reference values used for the preliminary economic assessment.

Material	LME reference (USD/t)	Approximate equivalent (EUR/t)
Aluminium	3,105.5	2,729
Copper	13,341.0	11,723

Reference date: late July 2026. Values are market benchmarks and do not represent actual scrap transaction prices.

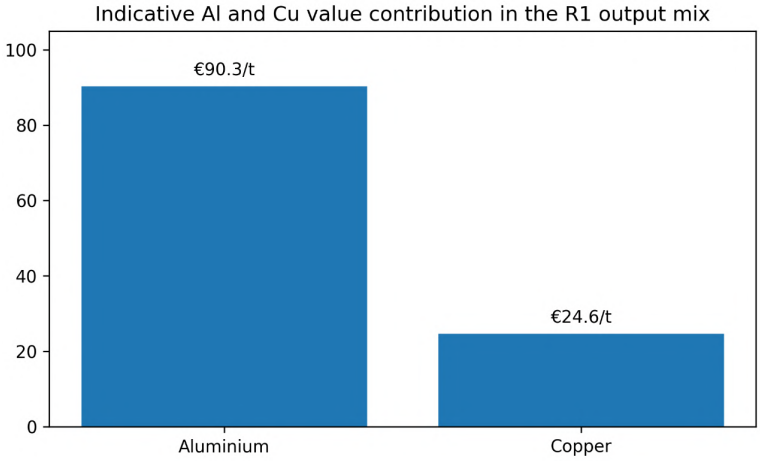
Using these reference values, one tonne of R1 material with the output composition reported in the company presentation would correspond to approximately 33.1 kg of aluminium and 2.1 kg of copper. The indicative gross metal-content value of these two fractions can be expressed as:

$$V_{\text{gross}} = \sum_i m_i P_i$$

where m_i is the mass of material fraction i, expressed in tonnes per tonne of treated WEEE (t/t), and P_i is the corresponding reference market price in EUR/t.

On this basis, aluminium contributes approximately 90.3 EUR per tonne of R1 treated, while copper contributes approximately 24.6 EUR per tonne. The combined indicative metal-content benchmark is therefore approximately 115 EUR per tonne of treated R1 material. This value should not be interpreted as plant revenue or profit, because it does not account for actual recovery yields, scrap discounts, operating costs, transport, treatment charges or the economic value of the other recovered fractions.

An important observation is that the copper fraction represents only 0.21% of the reported R1 mass but still accounts for more than one fifth of the combined aluminium–copper reference value. This illustrates why the recovery of relatively small quantities of copper can remain economically important and provides a practical justification for investigating further upgrading of the mixed Cu/Al fraction.



Annual-Scale Interpretation

The economic relevance of the R1 metallic fractions also depends on the annual amount of material treated by the plant. If Q_{R1} represents the annual R1 throughput in tonnes per year, the corresponding gross metal-content benchmark can be expressed as:

$$V_{\text{annual}} = Q_{R1} \times V_{\text{R1}}$$

where V_{R1} is the indicative aluminium–copper benchmark value per tonne of R1 material calculated above.

Since a publicly documented nominal annual capacity for the R1 line could not be identified, an annualized throughput scenario was also considered. During the industrial visit, a monthly R1 throughput of approximately 355 t was noted for March. If this monthly throughput were maintained over twelve months, it would correspond to an indicative annual throughput of approximately 4,260 t/y.

This value should not be interpreted as the nominal or authorized plant capacity, but only as an annualized operating scenario used to illustrate the economic scale of the R1 material flow.

Under this scenario, the aluminium and copper fractions reported in the company presentation would correspond to approximately 141.0 t/y of aluminium and 8.95 t/y of copper, or about 150 t/y of combined Al/Cu material. Using the reference metal values adopted in this study, the gross contained-metal benchmark would be approximately 0.49 million EUR/y.

Figure 5.3: Indicative gross metal-content value contribution of aluminium and copper per tonne of R1 material, calculated from the output fractions reported in the Transistor S.r.l. company presentation and late-July 2026 reference metal prices. The values represent market benchmarks and not actual plant revenues. *Source: author's elaboration based on [19, 22, 23].*

5.11.4 Economic Interpretation of the Electrostatic Separation Results

The economic relevance of electrostatic separation is not limited to the amount of copper recovered. An upgrading process can also create value by concentrating the target metal into a smaller product mass, thereby potentially reducing the quantity of material that must be transported, handled or subjected to subsequent refining operations. Bruch et al. identify product quality, recycling rate, process capacity, labour cost, energy cost and disposal cost as important economic criteria for WEEE fractionation [18].

The economic effect of the proposed treatment can also be interpreted in terms of value concentration. Using the copper reference price adopted in this study, the copper content of the initial machine-test feed corresponds to an indicative copper-content value density of approximately 1,116 EUR/t of material. This value increases to approximately 1,230 EUR/t in the 40 Hz copper-rich product, 3,510 EUR/t at 60 Hz and 6,777 EUR/t at 70 Hz. For the fraction smaller than 6.3 mm, the copper-content value density reaches approximately 8,806 EUR/t.

These values are not product selling prices. They represent only the theoretical market benchmark associated with the copper contained in each fraction. Their purpose is to show how the proposed treatment concentrates economic value into a smaller quantity of material.

A second useful indicator is the mass of copper-rich product generated per unit of copper recovered. Based on the experimental purity values, approximately 9.5 t of the 40 Hz product would contain one tonne of copper, compared with about 3.3 t at 60 Hz, 1.7 t at 70 Hz and approximately 1.3 t for the fraction smaller than 6.3 mm.

The reduction in product mass per tonne of contained copper may be economically relevant because it can reduce downstream handling, transportation and refining requirements. However, the actual saving depends on the commercial destination of the product and must be compared with the additional cost of the separation step.

The machine-test feed used in this thesis contained 9.52% copper. At 40 Hz, the copper-rich Bin 2 represented approximately 60.42% of the feed mass and had a copper purity of only 10.49%. The limited increase in copper concentration indicates that a large quantity of material would still need to be handled downstream for a relatively low product grade.

At 60 Hz, Bin 2 represented only 22.61% of the feed mass while containing 29.94% copper and recovering 71.48% of the copper. Compared with the original machine-test feed, this corresponds to an enrichment factor of approximately 3.14. This condition therefore combined relatively high copper recovery with a substantial reduction in the mass of the copper-rich product.

At 70 Hz, the copper-rich fraction represented only 10.62% of the feed mass and reached a copper purity of 57.81%, corresponding to an enrichment factor of approximately 6.07. From a valorization perspective, producing a much smaller and higher-grade product could reduce downstream material handling and may improve the suitability of the product for subsequent recovery operations. However, this advantage was accompanied by a reduction in copper recovery to 64.88%.

The proposed improvement also introduces additional costs. Following the cost-benefit framework applied to WEEE treatment by Achillas et al., these costs may include labour, energy consumption, equipment depreciation, maintenance, quality control and material handling [24].

For the present case, the additional treatment cost can be represented conceptually as:

$$C_{\text{additional}} = C_{\text{sieving}} + C_{\text{electrostatic}} + C_{\text{labour}} + C_{\text{maintenance}} + C_{\text{capital}}$$

and the incremental economic benefit of the proposed treatment can be expressed as:

$$\Delta V_{\text{net}} = R_{\text{proposed}} - R_{\text{current}} - C_{\text{additional}}$$

where R_{current} represents the value obtained from the existing mixed fraction and R_{proposed} represents the combined value of the separated Cu-rich and Al-rich products. Product quality is relevant because downstream metal markets generally apply technical specifications to recovered scrap. European end-of-waste criteria for copper and aluminium scrap explicitly link marketability to material quality and compliance with technical specifications [25, 26]. Therefore, the economic benefit of the proposed treatment is not determined only by metal mass recovery; the quality and usability of the separated products are also important.

Since the actual commercial selling price of the current mixed Cu/Al fraction was not available, a sensitivity approach was used instead of assigning an unsupported market price. The analysis considers how much additional value would be generated if the proposed upgrading route allowed the recovered products to capture a greater fraction of their theoretical contained-metal benchmark.

With an indicative Al–Cu benchmark of approximately 115 EUR per tonne of R1, a 5%, 10% or 20% improvement in captured material value would correspond to approximately 5.75, 11.50 and 23.00 EUR per tonne of R1, respectively.

As an order-of-magnitude reference for the energy component, a commercially available dry electrostatic separator reports installed powers of 3.0–5.5 kW for nominal throughputs of approximately 200–800 kg/h [27]. At the upper end of these throughput ranges, the corresponding electricity demand is approximately 6.9–7.5 kWh per tonne of material processed.

Using the 2025 EU average non-household electricity price of approximately 0.184 EUR/kWh as an external reference [28], the electricity component alone would correspond to roughly 1.3–1.4 EUR per tonne of Cu/Al material processed. This value is only an illustrative benchmark based on comparable commercial equipment and does not represent the actual operating cost of the Transistor plant. Labour, sieving, maintenance, depreciation, material handling and capital costs would still need to be considered.

Table 5.12: Sensitivity analysis of the potential value uplift associated with improved Cu/Al product quality.

Value uplift	EUR/t R1	EUR/y at 4,260 t/y	Break-even cost per t Cu/Al fraction
5%	5.75	24,495	163
10%	11.50	48,990	327
20%	23.00	97,980	653

Illustrative sensitivity scenarios. The annual values use the annualized 4,260 t/y R1 throughput scenario and should not be interpreted as predicted plant revenues.

Consequently, the 60 Hz and 70 Hz operating conditions represent different technical-economic strategies. The 60 Hz condition maximized copper recovery among the investigated one-pass tests, whereas the 70 Hz condition produced a smaller and considerably higher-grade copper-rich product. Determining which condition is economically preferable would require actual downstream product prices and processing costs, which were not available in the present study.

Table 5.13: Technical indicators relevant to the preliminary economic interpretation of the electrostatic separation tests.

Condition	Bin 2/feed (%)	Cu purity (%)	Cu recovery (%)	Cu enrichment
30 kV, 40 Hz	60.42	10.49	67.16	1.10
30 kV, 60 Hz	22.61	29.94	71.48	3.14
30 kV, 70 Hz	10.62	57.81	64.88	6.07

Source: author's elaboration based on the experimental results obtained in this study.

The particle-size classification results further strengthen this interpretation. For the fraction smaller than 6.3 mm, the copper-rich product represented only approximately 20.94% of the tested feed mass, while it contained 74.29% of the copper and reached a copper purity of 75.12%. In practical terms, almost three quarters of the copper present in that size fraction were concentrated into approximately one fifth of its original mass.

This concentration effect is potentially relevant from an economic perspective

because downstream operations would receive a smaller and substantially more copper-rich material stream. Nevertheless, sieving introduces an additional processing step and therefore additional equipment, energy and handling requirements. Its economic advantage would be confirmed only if the additional value or downstream cost reduction associated with the upgraded product exceeds the cost of size classification.

Current Situation and Proposed Treatment Improvement

The reference industrial situation considered in this study is represented by the mixed Al-rich non-ferrous fraction from which the laboratory sample was collected, before application of the additional size-classification and electrostatic upgrading route investigated in this thesis. In this intermediate material, copper remains distributed within an aluminium-rich fraction. Its economic value therefore depends on the quality, composition and commercial conditions applied to the material before any additional upgrading proposed in the present work.

The improvement proposed in this thesis is to introduce controlled particle-size classification followed by electrostatic separation of the suitable fine fractions. The aim is not to increase the total amount of copper or aluminium present in the material, but to redistribute them into products with higher metal concentration: a copper-rich fraction and an aluminium-rich fraction.

This upgrading may have two potential economic advantages. First, increasing the copper concentration increases the value density of the copper-rich product and reduces the mass that must be handled for each unit of recovered copper. Second, reducing copper contamination in the aluminium-rich fraction may improve its quality for downstream aluminium recycling, since copper is considered a relevant impurity in recycled aluminium streams [29]. Based on the experimental results, the proposed treatment sequence can be summarized as follows:

1. classification of the refrigerator-derived Cu/Al fraction by particle size;

2. electrostatic treatment of the fine and suitably liberated fractions;

3. collection of a concentrated Cu-rich product;

4. recovery of the remaining Al-rich fraction through the existing downstream aluminium recycling route;

5. optional re-processing of selected intermediate products when the additional copper recovery justifies the extra treatment effort.

Table 5.14: Comparison between the current mixed Cu/Al situation and the proposed additional treatment strategy.

Aspect	**Current situation**	**Proposed treatment**
Product structure	Mixed Al/Cu-containing fraction	Separate Cu-rich and Al-rich products
Particle-size classification	No additional classification for Cu/Al upgrading	Controlled sieving before electrostatic separation
Additional separation	No additional electrostatic Cu/Al upgrading step considered in this study	Electrostatic separation of suitable fractions
Copper concentration	Copper remains diluted in the mixed fraction	Copper concentrated into a smaller product mass
Aluminium quality	Aluminium remains associated with copper	Potential reduction of copper contamination in the Al-rich fraction
Potential revenue effect	Value determined by the commercial grade of the mixed fraction	Potential value increase associated with higher-grade separated products
Additional processing cost	Baseline industrial treatment	Sieving, electrostatic separation, handling, labour, energy, maintenance and equipment cost
Economic condition	Reference case	Favourable only if the additional product value and downstream savings exceed the additional treatment cost

Source: author's elaboration based on the experimental results obtained in this study and the economic framework discussed in [18, 24].

From an industrial implementation perspective, the proposed improvement would therefore be more appropriate as a selective treatment rather than as an additional electrostatic step applied to the entire Cu/Al stream. The mixed Cu/Al product leaving the existing R1 process could first undergo controlled particle-size classification, and only the fine and sufficiently liberated fractions could be directed to electrostatic upgrading.

This approach is supported by the experimental results, since the finest tested fraction produced the highest copper concentration and recovery. Coarser fractions would not necessarily need to pass through the additional separator and could remain in the existing downstream route or be treated using a more appropriate

mechanical or manual sorting method. Limiting electrostatic treatment to the fractions showing the greatest upgrading potential would reduce the mass processed by the additional equipment and could therefore limit energy, handling and equipment requirements.

Similarly, re-processing should be applied selectively rather than systematically. The laboratory tests demonstrated that additional copper can be recovered from an intermediate product, but a second pass would only be economically justified when the value of the additional recovered copper exceeds the associated processing cost.

5.11.5 Valorization Potential of the Small Electrical Devices Stream

The economic interpretation of the small electrical devices stream is more complex because the material is heterogeneous and contains both directly recoverable materials and composite components. The laboratory sample characterized in this study contained 57.88% aluminium, 4.00% copper, 4.42% printed circuit boards and a substantial mixed/residue fraction. These values describe the selected laboratory sample and should not be extrapolated directly to the total industrial R4 throughput.

The company presentation confirms, however, that the industrial R4 treatment route produces several fractions with potential economic value, including aluminium, copper, brass, electronic boards, cables, motors and transformers [19]. The Transistor S.r.l. commercial information similarly identifies metals, cables, motors, transformers and electronic boards among the materials that may be valorized [21].

Direct assignment of a single market price to printed circuit boards, motors, transformers or mixed electronic components would not be appropriate because their economic value depends on their detailed composition and grade. In particular, printed circuit board value can depend on the concentration of copper, precious metals and other recoverable elements, while composite components may require additional dismantling or processing before their metallic content becomes marketable.

For this reason, the main economic opportunity for the small electrical devices stream is not necessarily the application of the same electrostatic process used for the refrigerator-derived Cu/Al fraction. Instead, improved dismantling, component sorting and selective liberation could increase the proportion of material entering established high-value recovery routes while reducing the mixed/residue fraction. This confirms that the most economically appropriate treatment strategy depends on the characteristics of each WEEE stream.

5.11.6 Requirements for a Complete Industrial Feasibility Assessment

The present results demonstrate a clear potential for material upgrading, but they are not sufficient to calculate the profitability of an industrial electrostatic separation process. A complete feasibility assessment would require, at minimum, the industrial throughput of the Cu/Al fraction, actual purchase and sales prices for each product grade, electricity consumption, labour requirements, maintenance and equipment costs, costs associated with sieving and re-processing, transport costs and any disposal or treatment charges associated with residual fractions.

The economic benefit of an additional separation stage can be expressed conceptually as the difference between the additional value generated by the upgraded products and the additional cost required to produce them. Therefore, an extra sieving or electrostatic separation step is economically justified only when the improvement in product value or reduction in downstream costs is greater than its operating and capital cost.

This point is particularly important for the interpretation of the present results. Electrostatic separation does not create additional copper or aluminium; rather, it redistributes and concentrates the metals already present in the feed. Its economic role is therefore to produce fractions of sufficient quality and concentration to improve downstream valorization while maintaining acceptable recovery and limiting additional processing costs.

The refrigerator-derived Cu/Al stream appears to have the stronger potential for further process optimization because it is already a relatively concentrated non-ferrous fraction and can be upgraded using controlled particle size classification and electrostatic separation. The small electrical devices stream also contains valuable components, but its greater heterogeneity means that economic improvement is more likely to depend first on selective dismantling, sorting and liberation. These two cases illustrate that technical efficiency and economic valorization must be considered together when selecting treatment routes for different WEEE streams.

For an industrial decision, the most important additional data required from Transistor S.r.l. would therefore be the confirmed annual R1 throughput or nominal capacity, the actual selling value of the current mixed Cu/Al fraction, the selling prices obtainable for Cu-rich and Al-rich separated products, the electricity and labour requirements of the additional treatment, and the capital and maintenance costs of industrial-scale sieving and electrostatic equipment. These parameters would allow the preliminary analysis developed in this thesis to be converted into a full industrial cost-benefit assessment.

5.12 Chapter Summary

This chapter presented the experimental results obtained from the characterization and treatment of the selected WEEE-derived samples. The refrigerator-derived Cu/Al fraction was the main material used to evaluate electrostatic separation. The initial characterization showed that the sample was strongly aluminium-rich, but also contained a measurable amount of copper that could be targeted for recovery.

The initial electrostatic separation tests showed that drum frequency had a clear effect on the quality of the copper-rich product. At 30 kV and 40 Hz, the copper purity in Bin 2 was low. Increasing the frequency to 60 Hz improved the balance between copper purity and copper recovery, while 70 Hz produced the highest copper purity but with lower copper recovery. Re-processing of Bin 1 from the 60 Hz test recovered additional copper and confirmed the potential of multi-stage processing.

The most important improvement was obtained after introducing particle size classification by sieving. The refrigerator-derived Cu/Al fraction was divided into narrower size ranges, and the fine fractions below 10 mm were processed separately by electrostatic separation. The finest fraction, smaller than 6.3 mm, produced the best copper-rich product, with 75.12% copper purity and 74.29% copper recovery. This confirmed that sieving was a key feed-preparation step and one of the most important factors for improving separation performance.

The coarse Cu/Al size fractions were manually sorted because their larger particle size made visual identification more reliable. These fractions were mainly composed of aluminium, while copper was concentrated mostly in the 10–12.5 mm and 12.5–14 mm fractions. This showed that combining electrostatic separation for fine fractions with manual sorting for coarse fractions can provide a more complete characterization and treatment strategy.

Finally, the small electrical devices sample was manually characterized. This sample was not processed by sieving or electrostatic separation because it contained large, irregular and heterogeneous components that were not suitable for the available laboratory equipment. The results showed that aluminium was the dominant category, while the mixed/residue fraction represented a significant part of the sample. This highlighted the complexity of small electrical devices compared with the refrigerator-derived Cu/Al fraction.

The results demonstrate that electrostatic separation can improve copper concentration from WEEE-derived Cu/Al fractions, but the performance strongly depends on feed preparation. Particle size classification, appropriate operating conditions and possible re-processing of intermediate products are essential for improving copper purity and recovery.

The preliminary economic assessment also showed that the significance of the proposed treatment lies in upgrading the existing metal fractions rather than

creating additional metal recovery value from mass alone. On the basis of the company material composition and the adopted market benchmarks, the combined Al–Cu content of the R1 stream corresponds to an indicative value of about 115 EUR per tonne of R1 treated. An annualized throughput scenario based on the monthly value observed during the industrial visit gives an indicative scale of approximately 4,260 t/y, while the sensitivity analysis shows that even relatively small improvements in captured product value may become economically relevant at industrial throughput. The proposed improvement is therefore based on selective size classification and electrostatic upgrading of the most suitable fractions, provided that the additional value obtained exceeds the corresponding processing cost.

Chapter 6

Conclusions and Recommendations

6.1 Introduction

This chapter summarizes the main conclusions obtained from the characterization and treatment of the selected WEEE-derived samples. The work focused mainly on the recovery and concentration of copper from a refrigerator-derived Cu/Al fraction using electrostatic separation. In addition, a small electrical devices sample was manually characterized in order to compare the complexity of different industrial WEEE streams.

The results showed that electrostatic separation can be useful for upgrading a Cu/Al-rich non-ferrous fraction, but the performance of the process depends not only on the operating conditions of the separator. Feed preparation, and especially particle size classification by sieving, was found to be one of the most important factors affecting copper purity and recovery.

6.2 Main Conclusions

6.2.1 Industrial Relevance of the Selected Streams

The industrial case study showed that WEEE recycling produces several output fractions that may still contain mixed valuable materials after mechanical and physical treatment. In the refrigerator recycling line, the non-ferrous fraction contained both aluminium and copper. Although both metals are valuable, their separation is difficult because they are both conductive materials.

The refrigerator-derived Cu/Al fraction was therefore selected as the main experimental stream for electrostatic separation. The small electrical devices

sample represented a different type of WEEE stream. It was more heterogeneous and contained aluminium, copper, printed circuit boards, plastics, batteries and a large mixed/residue fraction. This comparison showed that different WEEE streams require different laboratory and treatment approaches.

6.2.2 Characterization of the Refrigerator-Derived Cu/Al Fraction

The initial characterization of the refrigerator-derived Cu/Al fraction showed that the sample was strongly aluminium-rich. The total initial mass was 3032.00 g, of which aluminium represented 2747.90 g, corresponding to 90.63%. Copper accounted for 205.80 g, corresponding to 6.79%, while waste/impurities represented 60.56 g, or 2.00%. The mass loss during manual characterization was limited to 17.74 g, equal to 0.59%.

These results confirmed that the selected sample was suitable for investigating copper concentration from an aluminium-rich non-ferrous fraction. The relatively low copper content also showed that the objective of the separation was not only to recover copper, but to concentrate it into a smaller copper-rich product.

6.2.3 Initial Electrostatic Separation Tests

The initial electrostatic separation tests were carried out on a representative machine-test feed of 355.00 g. The results showed that drum frequency had a clear effect on the separation behaviour. At 30 kV and 40 Hz, the copper-rich product had a copper purity of 10.49% and a copper recovery of 67.16%. Increasing the frequency to 60 Hz improved the copper purity to 29.94% and the copper recovery to 71.48%. At 70 Hz, the highest copper purity was obtained, equal to 57.81%, but copper recovery decreased to 64.88%.

These results showed that changing the operating parameters of the electrostatic separator affected the distribution of copper between the output bins. However, the initial tests also showed that machine settings alone were not sufficient to obtain a fully satisfactory separation. The broad particle size distribution and irregular particle shapes of the feed still limited the selectivity of the process.

6.2.4 Effectiveness of Re-Processing

Re-processing of Bin 1 from the 60 Hz test demonstrated the potential of multi-stage treatment. The re-processed feed had a mass of 258.63 g and still contained residual copper. After re-processing, Bin 2 had a mass of 15.72 g and contained 6.65 g of copper, corresponding to a copper purity of 42.30%.

This result showed that part of the copper remaining in an intermediate output fraction could be recovered through an additional separation step. Therefore, re-processing can be considered a useful strategy when a single separation stage does not recover all the valuable metal.

6.2.5 Role of Sieving and Particle Size Classification

The most important improvement in the experimental work was obtained after introducing sieving as a feed-preparation step for the refrigerator-derived Cu/Al fraction. The material was divided into different particle size classes, and the fine fractions below 10 mm were processed separately by electrostatic separation at 30 kV, 60 Hz and 10% feeder.

The finest fraction, smaller than 6.3 mm, produced the best copper-rich product, with 75.12% copper purity and 74.29% copper recovery. The 6.3–8 mm and 8–10 mm fractions also produced copper-rich products, but with lower copper purities of 58.04% and 53.43%, respectively.

These results confirmed that particle size classification was not only a characterization step, but a key pre-treatment operation. By reducing the variability of particle size within each test, the separation behaviour became more controlled and the copper-rich product became more concentrated. This finding is one of the central conclusions of the thesis: for real WEEE-derived Cu/Al fractions, a good separation performance requires both appropriate machine settings and proper feed preparation.

6.2.6 Manual Sorting of the Coarse Cu/Al Size Fractions

The coarse fractions larger than 10 mm were manually sorted instead of being processed by electrostatic separation. This approach was appropriate because the larger particles were easier to identify visually and their size made manual classification more reliable.

The coarse fractions were mainly composed of aluminium. The total aluminium mass in these fractions was 1541.17 g, while copper represented 71.42 g and waste represented 21.83 g. Copper was mainly found in the 10–12.5 mm and 12.5–14 mm fractions, while no copper was identified in the 16–20 mm and > 20 mm fractions.

This result showed that combining different approaches can be useful. Fine fractions were more suitable for electrostatic separation, while coarse fractions could be characterized effectively by manual sorting.

6.2.7 Manual Characterization of the Small Electrical Devices Sample

The small electrical devices sample was not processed by sieving or electrostatic separation. This decision was based on the large size, irregular shape and high heterogeneity of several components, which made the sample unsuitable for the available laboratory size-reduction, sieving and electrostatic separation equipment.

The total mass of the small electrical devices sample was 6297.60 g. Aluminium was the dominant category, with 3645.30 g, corresponding to 57.88% of the total mass. Copper represented 251.70 g, or 4.00%, while printed circuit boards accounted for 278.50 g, equal to 4.42%. The mixed/residue fraction was also significant, with 2059.30 g, corresponding to 32.70% of the sample.

The high mixed/residue content confirmed the complexity of the small electrical devices stream. This fraction included wires, capacitors, mixed copper–aluminium pieces and heterogeneous components that could not be reliably assigned to a single material category by simple manual sorting. This result highlighted that not all WEEE streams are directly suitable for the same separation procedure.

6.3 Overall Interpretation

The experimental results demonstrate that electrostatic separation can improve copper concentration from a refrigerator-derived Cu/Al fraction. However, the results also show that the efficiency of the process depends strongly on the condition of the feed. The initial tests confirmed that voltage and drum frequency are important operating parameters, but they are not sufficient by themselves to optimize the process.

The introduction of sieving changed the separation performance significantly. Processing narrower size fractions made the behaviour of the particles more controlled and produced higher copper purity, especially for the fraction smaller than 6.3 mm. This confirms that particle size classification is one of the main factors controlling the quality of electrostatic separation for real WEEE-derived fractions.

The comparison with the small electrical devices sample also showed that the applicability of a separation technology depends on the physical characteristics of the material. A relatively liberated Cu/Al particle fraction can be processed by electrostatic separation, especially after sieving. In contrast, a coarse and heterogeneous stream such as small electrical devices may require preliminary dismantling, size reduction or other preparation steps before machine separation can be considered.

From a practical and economic perspective, the results indicate that the refrigerator-derived Cu/Al fraction has the stronger potential for further valorization through controlled size classification and electrostatic separation. The

experiments showed that copper could be concentrated into substantially smaller product fractions while maintaining relatively high recovery, particularly under the 60 Hz condition and for the fraction smaller than 6.3 mm. This concentration may reduce the amount of material requiring downstream handling and improve the quality of the recovered metallic product. The small electrical devices stream also contained potentially valuable materials, but its greater heterogeneity suggests that selective dismantling, sorting and liberation would be more appropriate before any further separation stage. A complete assessment of industrial profitability would require plant-scale throughput, operating costs, energy consumption, labour requirements and actual sales prices for the recovered fractions.

6.4 Limitations of the Work

The work was based on real industrial samples, which is an important strength, but it also introduced some limitations. The material was heterogeneous and contained particles with different shapes, sizes and degrees of liberation. This made the results more representative of industrial conditions, but also increased the variability of the experimental data.

Another limitation was related to the amount of material available for laboratory testing. Some tests were carried out on relatively small masses after sampling and Riffle splitting. This means that the results should be interpreted as laboratory-scale evidence rather than as direct industrial-scale performance.

The electrostatic separation tests were also limited to selected operating conditions. Voltage, drum frequency and feeder setting were evaluated only within the available experimental range. Other parameters, such as splitter position, drum speed, electrode configuration, feed rate and material moisture, could also influence the separation behaviour but were not systematically investigated in this work.

For the small electrical devices sample, the main limitation was the impossibility of applying sieving and electrostatic separation with the available laboratory equipment. The sample was therefore characterized manually, but no machine separation performance indicators were calculated for this stream.

6.5 Recommendations for Future Work

Future work should further investigate the role of particle size classification in electrostatic separation. The results of this thesis showed that sieving improved the separation performance of the refrigerator-derived Cu/Al fraction, especially for the finest size fraction. Additional tests could be carried out on more size classes and with larger sample masses in order to confirm the reproducibility of the results.

A more detailed optimization of the electrostatic separator is also recommended. Future experiments could investigate the combined effect of voltage, drum frequency, splitter position, feed rate and electrode configuration. This would make it possible to identify more precise operating windows for maximizing copper purity, copper recovery or both.

Multi-stage processing should also be studied further. The re-processing test showed that additional copper could be recovered from an intermediate output fraction. Future work could evaluate systematic re-processing strategies, including repeated separation of Bin 1 or secondary cleaning of the copper-rich product.

For the small electrical devices stream, future work should focus on suitable pre-treatment methods. Since the sample contained large and heterogeneous components, preliminary dismantling, controlled crushing or component-level sorting may be necessary before applying sieving or electrostatic separation. Further characterization of the mixed/residue fraction would also be useful to understand how much valuable material remains in components that are difficult to classify manually.

6.6 Final Remarks

This thesis investigated the recovery of copper and aluminium from selected WEEE-derived streams by combining industrial observation, manual characterization, particle size classification and laboratory electrostatic separation. The work was based on real materials obtained from an industrial recycling context, and therefore reflected the practical complexity of WEEE treatment rather than an idealized laboratory mixture.

The results showed that the refrigerator-derived Cu/Al fraction was suitable for electrostatic separation, but that the separation performance depended strongly on both operating conditions and feed preparation. The initial tests demonstrated that changing the drum frequency affected the balance between copper purity and copper recovery. At 30 kV and 60 Hz, the best compromise between purity and recovery was obtained, while 70 Hz produced a higher copper purity but a lower recovery. The re-processing of Bin 1 further confirmed that multi-stage treatment can improve the concentration of copper in intermediate products.

A key outcome of the work was the importance of particle size classification. The initial electrostatic separation tests showed that machine parameters alone were not sufficient to obtain an optimized separation. After sieving, the fine size fractions could be processed more effectively, and the fraction smaller than 6.3 mm produced the best copper-rich product, with high copper purity and recovery. This confirms that feed preparation is a critical step for improving electrostatic separation of real WEEE-derived non-ferrous fractions.

The manual characterization of the small electrical devices sample provided a complementary view of another industrial WEEE stream. Unlike the refrigerator-derived Cu/Al fraction, this sample contained large, irregular and composite components, including PCBs, batteries, wires, capacitors and mixed metal–plastic pieces. For this reason, it was not suitable for the same laboratory separation procedure. This comparison highlights that the applicability of a recovery method depends not only on the material composition, but also on particle size, shape, degree of liberation and processability.

Overall, the thesis shows that electrostatic separation can be a useful technique for improving copper recovery from WEEE-derived Cu/Al fractions, especially when combined with appropriate pre-treatment steps such as sieving and possible re-processing of intermediate products. At the same time, the work confirms that real WEEE streams are highly heterogeneous and that the selection of the treatment method must be adapted to the physical characteristics of each stream. These results provide a practical basis for further optimization of non-ferrous metal recovery in WEEE recycling plants.

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