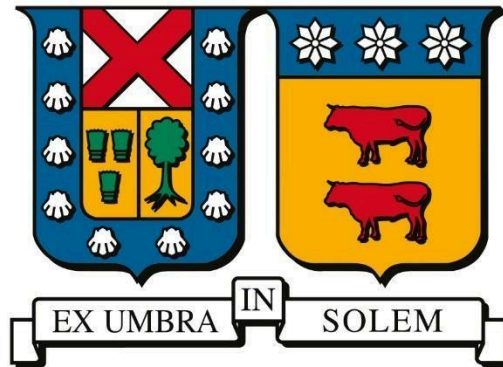


UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA

DEPARTMENT OF CHEMICAL AND ENVIRONMENTAL ENGINEERING

VALPARAISO, CHILE



**"Comparison Of Conventional And Advanced Sorting
Technologies For Mixed Residue Of Waste Electrical
And Electronic Equipments"**

Adil Rashid

**THESIS TO OBTAIN THE DEGREE OF MASTER
OF SCIENCE IN CHEMICAL ENGINEERING**

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VALIDATION AND CONFIDENTIALITY RECORD FOR
THESIS IN THE ACADEMIC REPOSITORY

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FOR MIXED RESIDUE OF WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT

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Comparison Of Conventional And Advanced Sorting Technologies For Mixed Residue Of Waste Electrical And Electronic Equipments

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DEGREE PROGRAMME EMJM-PROMISE

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MASTER'S THESIS



University of Zagreb
**FACULTY OF MINING
GEOLOGY AND
PETROLEUM
ENGINEERING**



UNIVERSITY OF ZAGREB
FACULTY OF MINING, GEOLOGY AND
PETROLEUM ENGINEERING

COMPARISON OF CONVENTIONAL AND ADVANCED SORTING TECHNOLOGIES FOR THE MIXED RESIDUE OF WASTE ELECTRICAL AND ELECTRONIC EQUIPMENTS.

Master's Thesis.

Adil Rashid
Zagreb, 2024

ABSTRACT

Title of the master's thesis: Comparison of conventional and advanced sorting technologies for mixed residue of waste electrical and electronic equipments.

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University of Oulu, Sustainable Mineral and Metal Processing Engineering

Master's thesis 2024

Supervisor(s) at the university: Dr. Gordan Bedekovic.

Every year about 83% of WEEE goes unrecycled. This amounts to a monetary value of around 47 billion USD. Because of this fact, there is a huge potential of recycling raw materials from this waste streams and at even higher recoveries. The aim of this research was to compare eddy current separation with optical separation for mixed residue of WEEE. A DoE is designed for Eddy current to find out the optimum separation parameters in relation to the independent variables. Feed material is tested with both the methods to make a comparison based on grade and recovery. The research showed that optical separation worked very efficiently for wires and glass, however for Al, Eddy current turned out to be better. Regarding Cu/Brass, both the processes had more or less similar results. Combining the two processes can prove to be a better option instead of using one of them.

Keywords: WEEE Recycling, Eddy Current Separation, Optical sorting, E-Waste, Resource recovery

FOREWORD

The thesis shows the research and analysis dedicated to WEEE to explore the performance of the sorting technologies namely eddy current separation and optical separation. The humongous increase in the amounts of waste presents an opportunity to recover metals and other valuable materials from this waste stream.

The thesis is developed in collaboration with Spectra media company and Faculty of Mining, Geology and Petroleum Engineering from University of Zagreb. It's mandatory for the fulfillment of the master's degree requirements and is funded by European Commission through PROMISE project.

I would like to thank my supervisor, Dr Gordan Bedeković for the guidance and support he has extended. I could not have wished for a better supervisor for my thesis. He made sure I had all the resources available at the laboratory for my test work. He was always available to answer my questions. I would also thank Mr. Oskar Ježovita from Spectra media company for providing me with the test samples and for an opportunity to use the optical separation facility in the company.

I would also extend my heartfelt gratitude to my family. They have been the source of support when I needed the most.

Zagreb, 10.05.2024

Adil Rashid

Author

TABLE OF CONTENTS

ABSTRACT	
FOREWORD	
TABLE OF CONTENTS	
LIST OF ABBREVIATIONS	
LIST OF ABBREVIATIONS	6
1. Introduction:	9
2. Literature Review:	12
2.1: Generation of WEEE:	13
2.2: Composition of WEEE:	15
2.3: Impacts of WEEE:	17
2.4: Regulations concerning WEEE:	18
2.4.1: Issues in WEEE Recycling:	19
2.4.2: WEEE Collection and recycling in Croatia:	19
2.5: WEEE Treatment process:	20
2.5.1: Density separation technique:	21
2.5.2: Magnetic separation technique:	22
2.5.3: Optical Separation:	22
2.5.3.1: Limitations of Optical Sorting:	23
2.5.4: Eddy Current Separation:	23
2.5.4.1: Limitations of ECS:	25
3. Research Process/Methodology:	26
3.1: Sample Preparation:	26
3.2: Analysis of Feed Sample Composition:	28
3.3: Optical Separation:	30
3.4: Eddy Current Separator:	32
3.4.1: Test Design:	33
3.5: Sieve analysis:	37
4: Results and Discussions:	38
4.1: Sieve Analysis:	38
4.2: Optical sorting results:	39
4.3: ECS Results:	44
4.4: Grade-Recovery Curve:	46
4.4.1: Relationship of Recovery to the independent variables:	46

4.4.2: Relationship of grade with the independent variables:	49
4.5: Separation of individual fractions:	52
4.5.1: Material Balance:	57
4.6: Comparison of ECS and OS:	59
4.7: Outlook:	61
5: Conclusions and Recommendations:	63
6: Summary:	64
References:	66

LIST OF ABBREVIATIONS

Al	aluminum
C	center point
Conc	concentrate
CRM	critical raw materials
Cu	copper
DoE	design of experiments
DV	dependent variable
D ₂₀	diameter at 20% cumulative passing
D ₈₀	diameter at 80% cumulative retained
ECS	eddy current separator
EEE	electrical and electronic equipment
EPR	extended producer responsibility
EU	european union
Hz	hertz
NIR	near infra-red
OS	optical separator
REE	rare earth elements
WEEE	waste electrical and electronic equipment
σ	electrical conductivity
μm	micrometers
mm	millimeters
ρ	density

List of Figures

Figure 1: Generation of EEE and WEEE. (Adapted from Forti, V. et al. 2020).....	13
Figure 2 Global amounts of WEEE recycled an unrecycled for year 2019. (Adapted from Forti, V. et al. (2020)).....	14
Figure 3: Elements contained in EEE/WEEE. (Adapted from O. Deubzer et al., 2020)	16
Figure 4: Average percentage of materials found in WEEE (Adapted from Van Yken et al., 2021).....	16
Figure 5: General Treatment of WEEE (Adapted from Ardi, 2016, Khaliq et al., 2014, Yken et al., 2021,).....	21
Figure 6: Optical sorting system. (Adapted from Hlostá et al., 2017).....	23
Figure 7: Working principle of ECS. (Adapted from Rao, 2007).....	24
Figure 8: Process flow at Spectra media / sample preparation process.....	28
Figure 9: Individual material fractions contained in the feed sample.....	29
Figure 10: Material composition comparison of the feed samples.....	30
Figure 11: Composition of feed samples.....	30
Figure 12: Feed sample for optical sorting process at spectra media.....	31
Figure 13: Independent variables for the ECS process (Adapted from MAGNAPower 2020).....	33
Figure 14: Composition of ECS concentrate from Run 7.....	36
Figure 15: Composition of ECS tailings from Run 7.....	37
Figure 16: Cumulative retained and passing percentages of average feed sample.....	39
Figure 17: Flowsheet of Optical sorting process at Spectra media.....	40
Figure 18: Wires concentrate (a) and glass concentrate (b) from optical separator at Spectra Media.....	42
Figure 19: Al concentrate from Optical separator at Spectra Media.....	43
Figure 20: Cu/Brass Concentrate from optical separator at Spectra Media.....	43
Figure 21: Grade-Recovery curve for the metals (Al and Cu/Brass).....	46
Figure 22: Fitted surface of recovery with rotor speed and belt speed.....	47
Figure 23: Fitted surface of recovery with rotor speed and splitter position.....	48
Figure 24: Fitted surface for recovery against the splitter position and belt speed.....	48
Figure 25: Observed and predicted values for recovery.....	49
Figure 26: Relationship of grade with rotor speed and belt speed.....	50
Figure 27: Fitted surface of grade against rotor speed and splitter position.....	51
Figure 28: Fitted surface of grade against splitter position and belt speed.....	51
Figure 29: Observed and predicted values for grade.....	52
Figure 30: Flowsheet for metals and other material separation by ECS.....	55
Figure 31: Recoveries of individual products in the relevant streams in ECS.....	57
Figure 32: Material balance and flow for ECS.....	59
Figure 33: Grade wise comparison of Optical separator and ECS.....	61
Figure 34: Recovery based comparison of Optical separator and ECS.....	62
Figure 35: Proposed flowsheet for optimum recovery of individual materials.....	63

List of Tables:

Table 1: Percentages of Electrical and Electronic Waste (Adapted from Ingólfssdóttir, 2019).....	12
Table 2. Sources of WEEE (Adapted from Ingólfssdóttir, 2019).....	13
Table 3: Amounts and values of materials in WEEE (Adapted from Liu et al., 2023)...	14
Table 4: Harmful impacts of WEEE on human health (Adapted from Pavindra, 2016).	17
Table 5: Yearly placed on market and collection rates in Croatia (Malic, 2023).....	20
Table 6: Deflection coefficients of metals and materials (Adapted from Yazici et al., 2010).....	25
Table 7: Average composition and weight percentages after manual sorting of feed samples.....	29
Table 8: Weight percentages of Optical sorting products.....	32
Table 9: Optimum conditions for the preliminary test work using ECS.....	34
Table 10: Coded and real values of the independent variables.....	35
Table 11: Test plan for ECS using DoE.....	35
Table 12: Sieve analysis for the average Feed sample.....	38
Table 13: Weights of the concentrates separated by optical sorting at spectra media....	40
Table 14: Grade and Recovery of individual elements in different stages of OS.....	41
Table 15: Grade and recovery for all the 17 test runs after ECS.....	45
Table 16: Separation percentages of Al and Cu in concentrate and tailing.....	53
Table 17: Separation percentages of Glass and stones.....	54
Table 18: Separation percentages of Wires and composites.....	54
Table 19: Recoveries of individual materials in Concentrate or Tailings.....	56
Table 20: Material Flow and Balance for tests 18-21.....	58
Table 21: Grade and Recovery of individual products after optical separation.....	59
Table 22: Grade and Recovery of individual products after ECS.....	60
Table 23: Grade Recovery Comparison of ECS and OS.....	61

1. Introduction:

In this digital age, we are surrounded by handful of devices which we are using in our day-to-day life. Electrical and Electronic Equipment (EEE) have definitely made our lives easier. But once these devices reach the end of their useful life, their disposal and recycling become a challenge. The technology is progressing at a rapid pace. And because of the advancing and rapidly changing technology, the electrical and electronic Equipment (EEE) are developing very fast. So, more and more waste electrical and electronic equipment (WEEE) are being produced. Production of EEE requires variety of scarce metals along with the base metals (Andersson et al., 2019). A computer hard drive contains 48 different metals (Buechler et al., 2020).

Because of the massive growth in the electronic industry, the amount of the waste associated has risen sharply. This waste stream is commonly termed as Waste Electrical and Electronic Equipment (WEEE). Material-wise, WEEE is one of the most complex waste streams (Andersson et al., 2019). Besides base and precious metals and plastics, WEEE contains hazardous elements like lead, cadmium and mercury as well (Hu et al., 2011).

WEEE contains Rare Earth Elements (REE) like neodymium, europium, terbium, yttrium, cerium and gadolinium. These REEs have been classified to be Critical Raw Materials (CRM) (Batinic et al., 2018). The pressure being exerted on the natural resources and the principles of sustainability demand to move from a linear model towards a circular economy model (Andersen et al., 2020).

A huge amount of the WEEE ends up in landfills and is not recycled (Hadi et al., 2015). This means that the valuable materials contained in them are lost as well which amounts to a high value in monetary terms (Forti, V. *et al.*, 2020). Because of the pressure being exerted on the natural resources and criticality of certain metals, WEEE provides us with an opportunity to recover raw materials from them. WEEE is a secondary source of raw materials. This thesis will help in focusing more on recycling of all kinds of materials from WEEE instead of recycling just the plastics. The resources which end up undocumented and un-recycled present an opportunity to recover valuable raw materials and add them into the loop again considering the principles of circular economy.

The growing concern and challenge are the rapid and humongous growth of WEEE (Andersen, 2021) however the collection rates are quite low, and the waste recycling facilities do not have the capacity to cope with the volumes generated (Ferronato & Torretta, 2019). Technically, the biggest challenge in WEEE recycling is to separate this complex mixture of metals, plastics and other materials (Friedrich & Pretz, 2012). And those materials are embedded into each other (Friedrich & Pretz, 2012). Because of the complexity and diversity of materials contained in WEEE, recycling becomes difficult. Only 40-50% of the collected volumes are recycled (Chaine et al., 2023).

Conventionally, the focus had been on recovering plastics from WEEE as it constitutes a major part of WEEE. And to recover plastics, mostly optical or sensor-based sorting techniques are being utilized in the industry. TOMRA, one of the biggest players in the plastic waste recycling, works with optical sorting (TOMRA Recycling, 2024).

But with this study the focus would be to look for a method for efficient separation of metallic and non-metallic fractions. To find out which process has a better separation efficiency or if we should be using a combination of the two processes to separate plastics and metals. The metallic fraction can thus be subjected to further processing techniques to recover individual metals in a later study.

Recycling of WEEE comes along with the sustainability principles both economically and environmentally. Recovering raw materials from WEEE generates revenues and creates jobs. At the same time, it reduces the environmental impact caused by open incineration or landfilling of WEEE. Recycling raw materials from this secondary source also requires less energy as compared to the primary raw materials (Van Yken et al., 2021).

It has been shown by studies that the strength of recycled plastics decreases, either due to number of time it has been recycled or due to the presence of impurities. So, effective separation and sorting techniques are indispensable (Maisel et al., 2020).

Developed countries have been exporting their WEEE to the developing countries. At the same time, the developing countries lack the infrastructure to handle that waste (Liu et al., 2023). Thus, most of the waste ends up being burnt openly or is dumped in landfills. Besides lack of legislation regarding WEEE, developing countries lack in knowledge about the hazardous nature of the waste being sent to their countries (Ferronato &

Torretta, 2019). This way the developing countries face twice the pressure, of generation at home and the illegal imports (Li et al., 2017).

In this thesis, the conventional method (eddy current separator, ECS) and the advanced sorting method (optical separator) were used to sort the mixed residue of WEEE. The two techniques were compared based on their separation efficiency and how well they work to separate metallic and non-metallic fraction from each other. The main goal of this thesis was to compare these two processes based on their separation efficiency. To find out an optimum process for separating metallic and non-metallic fraction. To find out a recovery wise efficient technique for separation of metals and non-metals from WEEE with minimum losses. This information then can be used to recover the metals individually using different separation techniques in a later study.

The thesis was carried out at Spectra media under the supervision of Oskar Ježovita and at Faculty of Mining, Geology and Petroleum Engineering at University of Zagreb under the supervision of Dr. Gordan Bedeković. Optical sorting technique was tested at the company Spectra media. While ECS technique was tested at the Laboratory in the University of Zagreb. Both the techniques were then analyzed for the efficiency of recovery.

The test sample was analyzed with optical sorting technique to get results. The same sample was then tested by ECS at the faculty. The results of both the tests were compared to see which technique works better for the mixed residue of WEEE. Comparisons and conclusions were made based on the test results. Recovering metals and plastics from the mixed residue

With this research an effort was made to efficiently separate metals and plastics from the mixed residue and then use this knowledge later to extract metals from the metallic fraction.

2. Literature Review:

All the equipment which depend on electric current or electromagnetic field to function are termed as electrical and electronic equipment (EEE). It also includes the equipment to generate, conduct and measure those currents and fields. These equipment cannot have a voltage rating over 1000 volts for alternating current and 1500 volts for direct current (EU Directive, 2012). WEEE is the waste that is any part of the electrical and electronic devices which is no longer useful and have been discarded (Kaya, 2016). WEEE is also commonly referred to as e-waste in Europe. WEEE is divided into two main categories namely Electrical equipment and electronic equipment. Both the categories account for around 50% of the waste generated that contributes to WEEE (Ingólfssdóttir, 2019). Table 1 shows the percentage amounts of subcategories of electrical and electronic waste. Heat exchange equipment include refrigerators, freezers, air conditioners etc. While large equipment include washing machines, tumble dryers, dishwashers, and electric stoves. According to the EU waste directive, the goal is to prevent the generation of waste. The necessary order follows re-use, recycling, and recovery (Andersen, 2021).

Table 1: Percentages of Electrical and Electronic Waste (Adapted from Ingólfssdóttir, 2019).

Electrical Waste	%
Heat Exchange Equipments	20
Large Equipments	30
Electronic Waste	%
Monitors	10
Televisions	10
DVD/VCR/CD player, Radio	15
Computers, mobiles	15

Usually, the sources of WEEE are homes, hospitals, government, and private sectors. Table 2 shows the sources of WEEE depicted in these four categories and the type of the equipment.

Table 2. Sources of WEEE (Adapted from Ingólfssdóttir, 2019).

Homes	Hospitals	Government	Private sector
Mobile Phones	Computers	Computers	Computers
Computers	Monitors	Printers	Boilers
TV Screens	Xray machines	Fax Machines	Mixers
Washing machines	MRI	Lights	Incubatorss
Refrigertaors	ECG/EKG	Fans	Signal conditioners
Electric irons	Printers	Photocopiers	
Fanss	Airconditioners	Airconditioners	

2.1: Generation of WEEE:

With increasing urbanization/industrialization and higher amounts of incomes at disposal, a lot of EEE are being produced every year. At the same time, because of the shorter product life, technological advancements, and fewer repair options, we are generating way too much WEEE (Huang et al., 2021). Fig 1 shows the schematics of the factors contributing to the generation of EEE and WEEE.

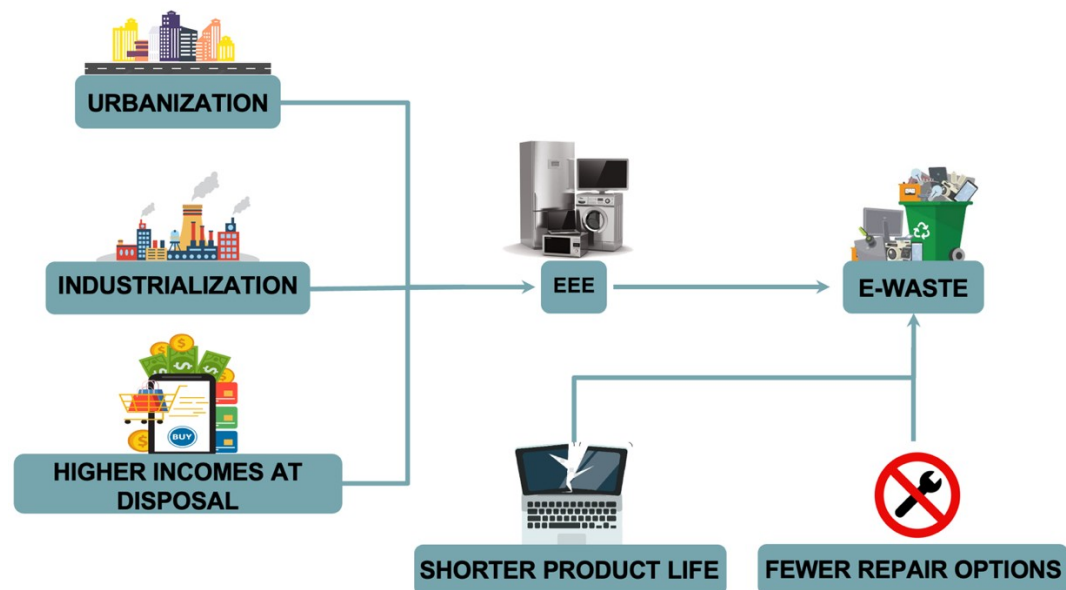


Figure 1: Generation of EEE and WEEE (Adapted from Forti, V. et al. 2020).

In year 2019, the amount of global e-waste produced was about 53.6 million tonnes and the amount is expected to double by 2030 (Forti, V. *et al.*, 2020). The generation of WEEE is growing at a projected rate of 2 million tonnes (Chaine et al., 2023) which corresponds to a rate of about 4% per year (Bressanelli et al., 2020). WEEE stream is growing even faster than municipal waste (Lahtela et al., 2022). WEEE produced in 2019 was

equivalent to a value of 57 billion USD (Forti, V. *et al.*, 2020). Because of these high economic values, WEEE is referred to as urban mine as well (Jadhao *et al.*, 2023). Just 17.4% of WEEE was collected and recycled which corresponds to an amount of 9.3 million tonnes and a monetary value of 10 billion USD. While 82.6% of WEEE went undocumented and was not recycled (Pan *et al.*, 2022). About 47 million USD worth of raw material ended up in landfills. This can be seen in Fig 2 which shows the amounts of WEEE generated and how much of it was recycled. While table 3 shows the amounts in tonnes and values in billion euros of individual material. Recycling 17.4% of WEEE in 2019 helped to reduce 15 Mt of CO₂ equivalents in emissions and about 4 Mt of raw materials (Forti, V. *et al.*, 2020).

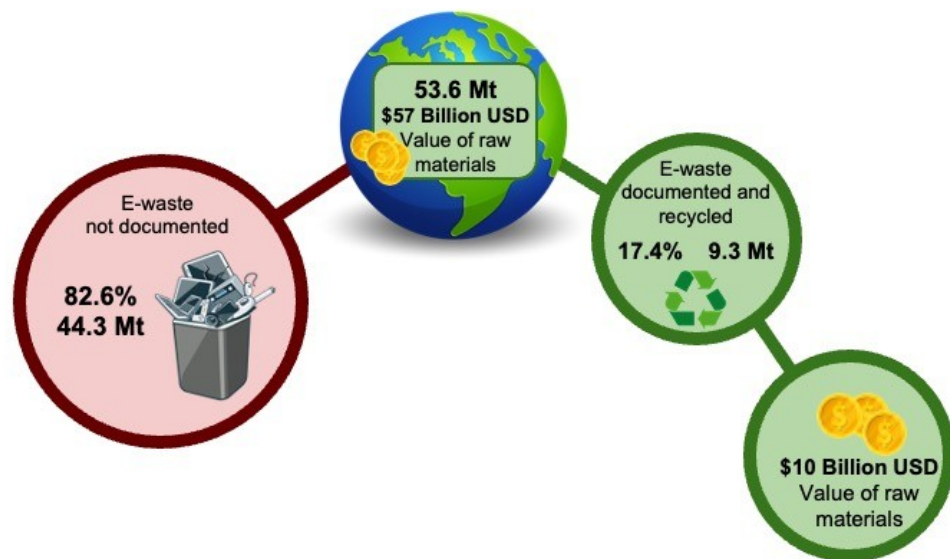


Figure 2 Global amounts of WEEE recycled and unrecycled for year 2019. (Adapted from Forti, V. *et al.* (2020)).

Table 3: Amounts and values of materials in WEEE (Adapted from Liu *et al.*, 2023).

Material/Metal	Amount (t)	Value (Billion Euros)
Iron/Steel	16500000	9
Copper	1900000	10.6
Aluminum	220000	3.2
Gold	300	10.4
Silver	1000	0.58
Plastics	8600000	12.3

The per capita WEEE generation increased from 6.4 kg in 2014 to 7.3 kg in 2019 (Forti, V. *et al.* (2020)). Composition wise, WEEE are very complex (Hubau *et al.*, 2019, Liu *et*

al., 2023). WEEE contains around 69 elements from the periodic table in varying amounts and depending on the equipment (O. Deubzer et al., 2020). Composition of WEEE depends on the location, type of equipment and the year of production (Hubau et al., 2019). According to studies, WEEE contains from 15 % (Gulliani et al., 2023) to 20 % (Van Yken et al., 2021) of plastics.

Although several studies were made regarding the metallurgical process development to recover metals, yet little or no data is available in literature (Hubau et al., 2019).

2.2: Composition of WEEE:

WEEE also contain base and precious metals like gold, iron and silver, precious metals like platinum, palladium and cobalt. It also contains iron and aluminum (Andersen et al., 2020). Strategic and critical raw materials like copper and nickel are also present in WEEE (Ghisellini et al., 2023). Besides the metals of interest, it also has some toxic metals and substances like lead, chromium, cadmium, mercury, polybrominated biphenyl and polybrominated diphenyl ether. These substances are harmful not only to human health but also to the animal and aquatic life (Lahtela et al., 2022). The hazardous substances must be limited below the designated values as per the Restriction of hazardous substances Directive (RoHS) (Lahtela et al., 2022).

The production of WEEE depends on base metals and also on some of the critical raw materials which are produced only in a few locations around the globe (Andersson et al., 2019). Not all metals are recycled from WEEE in a way that ensures their distinctive properties to be used again so they end up in landfills or being dispersed in other materials (Andersson et al., 2019). WEEE or e-waste can contain up to 60 different kind of metals (Liu et al., 2023). The elements of the periodic table contained in various EEE can be seen highlighted in the Figure 3.

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57-71 Lanthanides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89-103 Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Ununtrium	114 Fl Flerovium	115 Uup Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 Uuo Ununoctium
Lanthanides		57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
Actinides		89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	

Figure 3: Elements contained in EEE/WEEE. (Adapted from O. Deubzer et al., 2020)

However, Figure 4 shows the average composition of the different types of materials present in the WEEE. On average, WEEE contains about 61% of metals, 20% of plastics and varying amounts of glass, ceramics, wood, and rubber-based materials.

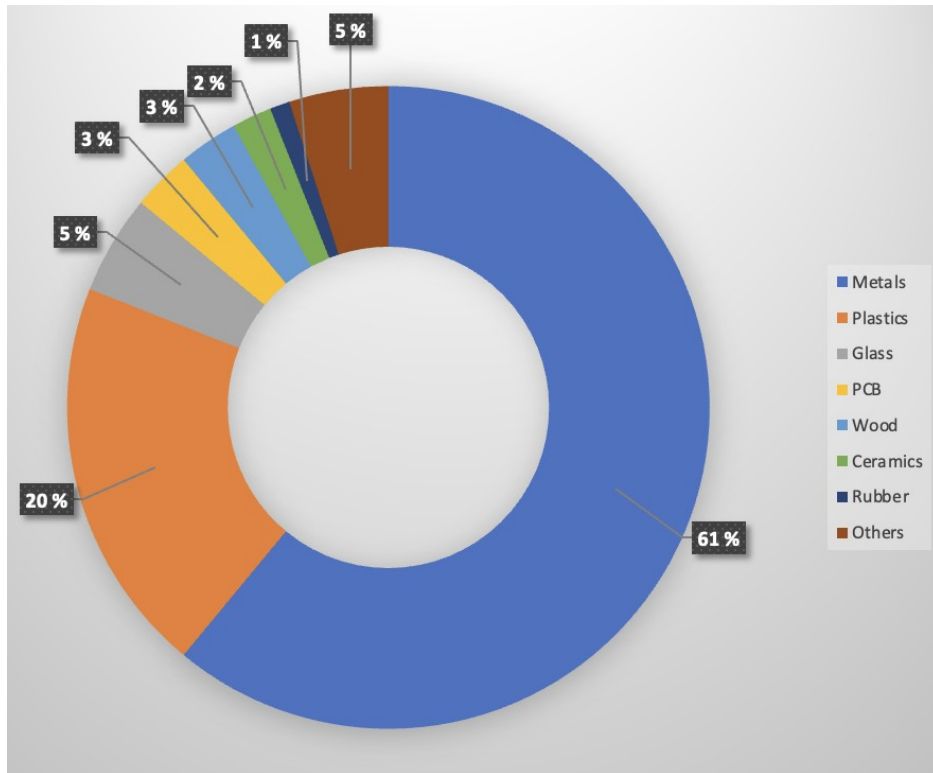


Figure 4: Average percentage of materials found in WEEE (Adapted from Van Yken et al., 2021).

2.3: Impacts of WEEE:

As about 83% of WEEE is not recycled (Forti, V. *et al.*, 2020) so this amount ends up in landfills (Hadi et al., 2015). WEEE contains polymers which are hazardous because of their limited degradability (Diedler et al., 2018). WEEE has materials of economic value but at the same time it poses serious environmental threats in case of improper and unregulated disposals (Vermeşan et al., 2019). If disposed off directly to the environment, these hazardous materials from WEEE can have serious impacts on environment. And at the same time, they pose threats to human health (He & Duan, 2017). The heavy metals and the harmful substances from WEEE contaminate air, soil and water. This leads to soil contamination and eventual contamination of the surface and ground water bodies (Vaccari et al., 2019, Wang & Xu, 2014).

WEEE, due to its composition fails to comply with the Toxicity characteristic leaching procedure (TCLP) because of the high amount of lead leaching out. (NIU & LI, 2007). Because of incineration or acid leaching treatment of WEEE in developing countries, the workers and residents reported significant amounts of pollutants and hazardous substances in their bodies (Vaccari et al., 2019). The metal recovery from WEEE is mostly done by leaching, pyrolysis, or hydrometallurgical processes. All these processes produce environmentally unfriendly gases (Hadi et al., 2015). A study by (Ghisellini et al., 2023) showed that recovering metals from WEEE generates less environmental impacts than producing those from primary mining. Table 4 shows the possible harmful effects that constituents of WEEE have on human health.

With metals being primarily mined from the natural deposits, WEEE presents us with an opportunity to recover metals in a circular economy approach and thus to use them again. Besides metal mining is expensive and has higher environmental impact as well (Jadhao et al., 2023).

Table 4: Harmful impacts of WEEE on human health (Adapted from Pavindra, 2016).

Source of e-waste	Constituents	Health Impacts
Chip resistors and semiconductors	Cadmium (Cd)	Causes neural damage, accumulates in kidney and liver
Solder in PCBs, glass panels, gaskets	Lead (Pb)	Damage to central and peripheral nervous system, affects brain development in children
Relay, switches, PCBs	Mercury (Hg)	Chronic damage to brain, respiratory and skin disorders
Corrosion protection of untreated steel	Hexavalent Chromium (Cr)VI	DNA damage, Asthmatic bronchitis
Cables and computer housing	Plastics PVC	Immune system damage, interferes with regulatory hormones, Reproductive and developmental problems
Plastic housing	Brominated Flame Retardants (BFR)	Disrupts endocrine system functions
Front panel of CRTs	Barium (Ba)	Muscle weakness, damage to heart liver and spleen
Motherboard	Beryllium (Be)	Carcinogenic, skin diseases such as warts, beryllicosis

2.4: Regulations concerning WEEE:

Because of certain directives and regulations, recycling of e-waste is indispensable. One of the most important regulation that forces the producers to facilitate and recycle is Extended producer responsibility (EPR). EPR has been enforced in Europe since 1990s. The main reason of this regulation was to shift the financial burden from the municipalities to the producers for waste management. It also encouraged producers to recycle and use more secondary resources instead of primary raw materials. This also made the producers rethink the design of the products, so they are able to manufacture products with less material and in a way to reduce waste (Cahill et al., 2010). EU WEEE Directive and Restriction of Hazardous substances in EEE (RoHS) also emphasize on efficient processing and recycling of WEEE (Diedler et al., 2018). It's not only the presence of valuable materials in WEEE that present a compelling reason for recycling but also the presence of hazardous substances that dictates how these materials are handled (Berežni et al., 2021).

2.4.1: Issues in WEEE Recycling:

Technically, the biggest challenge in WEEE recycling is to separate this complex mixture of metals and plastics etc. (Friedrich & Pretz, 2012). For recycling to work at an industrial scale, a continuous and constant flow of WEEE is needed (Ghisellini et al., 2023). For that, collection is critical for WEEE hierarchy (Vaccari et al., 2019). Shredding is more appropriate for WEEE because crushing can cause an increase in the size due to heat dissipation and cluster formation (Hubau et al., 2019).

Besides a high value of precious metals, separation technologies and the presence of toxic substances lower the material recovery from WEEE (Hadi et al., 2015). Obtaining a sample that is both representative and reproducible from WEEE is extremely challenging because of the heterogeneous nature of the material (Hubau et al., 2019). In developing countries, there is a lack of regulations to deal with WEEE. Also, there is no infrastructure, and the society has limited awareness of the impacts of this waste stream (Berežni et al., 2022).

2.4.2: WEEE Collection and recycling in Croatia:

According to the WEEE directive the target for waste collection is 65%. Croatia is complying with the directive and is doing well. In Croatia, the producers must pay the fee for placing the EE equipment on the market. A monetary value of 0.3 Euro/Kg has to be

paid by the producer because of the EPR. Table 5 below presents the data of WEEE collected and recycled in Croatia. In 2020, about 41696 tonnes were collected at a rate of 10.1 Kg per inhabitant and 39964 tonnes were processed. Similarly in year 2021, 37225 tonnes were collected at a rate of 9.2 kg per inhabitant and 36143 tonnes were recycled. The drop in the target is associated with the reduction in the weight of the large devices discarded by the population as compared to the previous years. Also, there is improvement in the data of EPR system regarding placement of EE in market.

Table 5: Yearly placed on market and collection rates in Croatia (Malic, 2023).

Year	Placed on market (POM)(t)	POM expressed as average of last 3 years (t)	Collected (t)	Recycled (t)	Collection rate %
2011	45642	56553	17518	16808	31
2012	39663	47951	16187	16493	34
2013	40034	43633	15025	13647	34
2014	39169	41780	15488	15213	37
2015	44702	39622	23758	21993	60
2016	50131	41302	38815	37484	94
2017	54395	44667	36434	34812	82
2018	61302	49743	41523	37878	83
2019	61592	55276	40400	37922	73
2020	66505	59096	40792	38851	69
2021	74150	63133	35477	32786	56

2.5: WEEE Treatment process:

The WEEE, that ends up in developing countries, usually undergoes the informal and unregulated recycling process. Most of the world's documented WEEE is treated in low-income countries like India, China, Pakistan, Ghana, Nigeria, Brazil and Uruguay. Majority of this WEEE is treated on huge waste dumping sites or in small shops. The material is either burnt in open fires to extract metals or is treated with chemicals and solvents. Finally, the residual is burnt again (Ádám et al., 2021). However, in formal WEEE recycling, the materials are recovered and provided to the consumers.

A formal WEEE treatment process in general consists of three main steps which are collection, pre-treatment and processing. Once discarded WEEE must undergo these processes for the materials to be recycled (Van Yken et al., 2021). One of the biggest issues in recycling of WEEE is collection. To comply with the waste hierarchy for recycling, collection is crucial (Vaccari et al., 2019). After collection, WEEE is subjected to the pre-treatment processes which involve sorting and dismantling. In developing countries, manual disassembly of WEEE is being practiced because of the less strict regulations. In this type of dismantling, the PCBs are heated to high temperatures to melt the materials and then to pick up the desired components with pliers. While in developed countries, selective mechanical dismantling is used. It is also referred to as look and pick method where material is picked and detached selectively. After dismantling, WEEE is subjected to comminution and shredding process. Here, the size of the material is reduced using crushing and cutting equipment. Comminution is followed by sieving which allows to characterize material in different size classes. And finally, the physical separation techniques are employed (Gulliani et al., 2023). Fig 5 describes a general WEEE treatment process that begins with waste collection followed by sorting and dismantling. Once the material has been sorted, it is subjected to the shredding stage where the size of the material is reduced to allow for the subsequent processes to work effectively. Magnetic separation can be used to separate ferrous metals from the mixture while eddy current or optical sorting techniques can be used to separate the non-ferrous metals from plastics. The metals are then subjected to various processing techniques to recover them. According to Andersson et al., 2019 in Sweden the metallic fraction is then sold to the smelting plants. Automated and continuous crushing comes out to be a better process than manual dismantling of small household appliance like cell phones (Li et al., 2017).

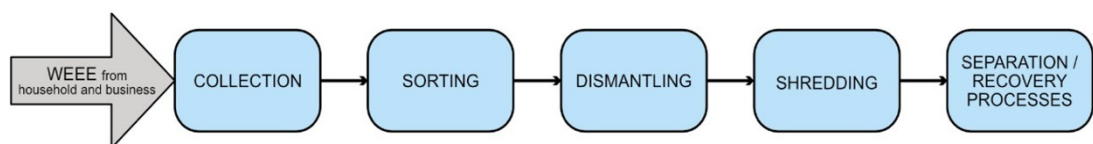


Figure 5: General Treatment of WEEE (Adapted from Ardi, 2016, Khaliq et al., 2014, Yken et al., 2021,)

Generally, the physical separation techniques depend on the type of material to be separated. There is no single technique to separate all the materials in the mixed residue of WEEE. So, the choice of the technique to be used depends on the material to be separated.

2.5.1: Density separation technique:

This technique uses density to characterize particles. Density separation processes can be either dry or wet based. In wet process, the material is allowed to pass through a liquid medium. The particles with higher density settle faster as compared to the lighter particles. The particles with lower density take a longer time to sink while the particles lighter than the liquid start floating on the surface of the liquid (Hlosta et al., 2017).

2.5.2: Magnetic separation technique:

Magnetic susceptibility of the materials allows us to separate ferrous metals from the rest of the material. The material to be separated is passed through a conveyor belt over a magnetic rotor. The magnetic particles move closer to the conveyor belt due to the magnetic field of the rotor while the non-magnetic particles fall over the splitter into the collection bin (Gulliani et al., 2023). Agglomeration of the non-metallic fraction is one of the biggest issues in magnetic separation (Hadi et al., 2015).

2.5.3: Optical Separation:

Optical sorting is a sensor-based sorting technique. The material to be analyzed is passed over a conveyor belt under a light source. The material has to be spread as a single layered material on the belt. The material passing under the light source is detected by the Near Infrared Technology (NIR). Each material has characteristic infrared spectrum, which allows detection of the material. The system is already fed with the separation threshold values. When the material to be separated is detected the system activates the air-jets or the deflecting mechanism to eject the material out of the stream. The rest of the material falls into the reject bin (Hlosta et al., 2017). The wavelength range of NIR is between 700 and 2500 nm. NIR sorting has the capability of identifying 1000 spectra of polymers per second. Optical sorting can distinguish color or shape of the particles. Optical sorting is not that effective when separating mixed streams of WEEE. However, if the stream contains single source, then this method is quite effective (Cherrington & Makenji, 2019). Figure 6 shows how an optical sorting system works.

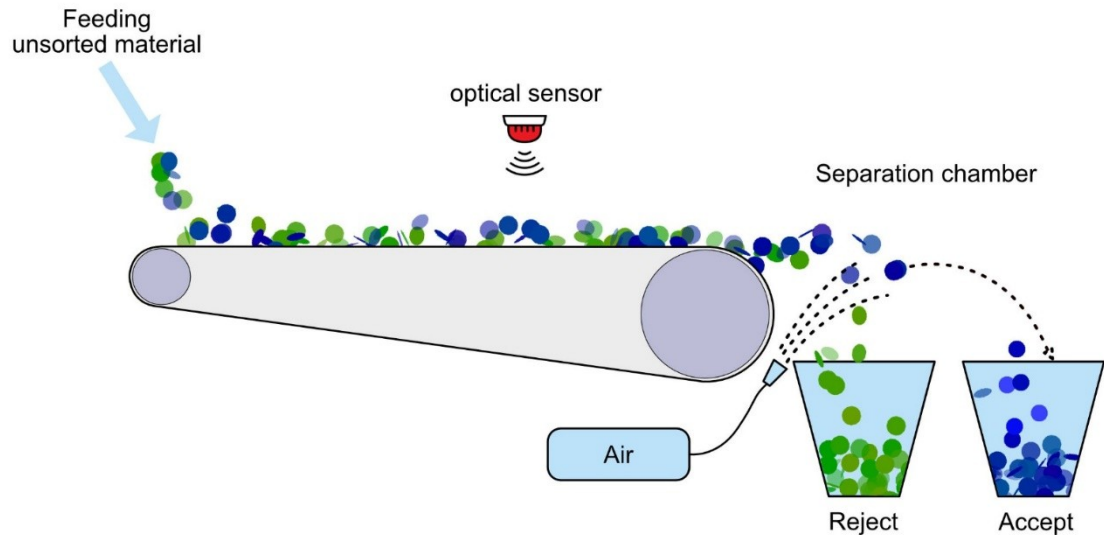


Figure 6: Optical sorting system. (Adapted from Hlosta et al., 2017).

2.5.3.1: Limitations of Optical Sorting: An optical sorter is unable to distinguish between different materials of same color. It is also inefficient in recognizing same material of different colors. When the material stream contains a lot of different types of material then the process becomes inefficient. To process that material, several cycles must be run in order to get the material sorted. This can be very time consuming. So, in case of inhomogeneous streams, the process is less efficient (Stubicar, 2022).

2.5.4: Eddy Current Separation:

Eddy current separation is based on the Faraday's law of electromagnetic induction and the interaction of the alternating magnetic field with the induced magnetic field to produce a repulsive force (Rao, 2007). The conductor metals upon interaction with the main magnetic field develops a current known as eddy current. This eddy current induces a magnetic field in those metal particles and this magnetic field is opposite to the main magnetic field. This generates a repulsive force known as Lorentz force on these metal particles. As this force is smaller in magnitude compared to the main magnetic field. These metal particles get deflected away from the drum and the conveyor belt. This repulsive force F is given by the relation (Wang et al., 2013).

$$F \propto H^2 f \nu \sigma / s$$

Where,

H is the alternating magnetic field intensity

f is the frequency of the alternating magnetic field

v is the volume of the metal particle

σ is the electrical conductivity of the metal

s is the shape factor of the metal

Considering the magnetic field intensity, frequency of magnetic field, volume of metal and shape factor of metal to be constant, this repulsive force is dependent directly on the electrical conductivity of the metal. Thus, different metals with different electrical conductivity will produce different repulsive forces. This mechanism is used to separate non-ferrous and conductive materials from a mixed metal stream (Wang et al., 2013).

Fig 7 shows the basic working principle of the ECS. As soon as the conductor material approaches the magnetic field of the rotor, the induced magnetic field developed in conductor is such that it opposes the main magnetic field. Thus, they are deflected away from the magnetic rotor. And if there are magnetic particles, then the magnetic field induced in those particles reinforces the main magnetic field and they move in contact with the belt. While the non-magnetic, non-conducting materials fall off the belt under the force of gravity. The splitter position, speed of the rotor, belt speed, feeding method are some of the factors that influence the process of separation and dictate the design factors as well.

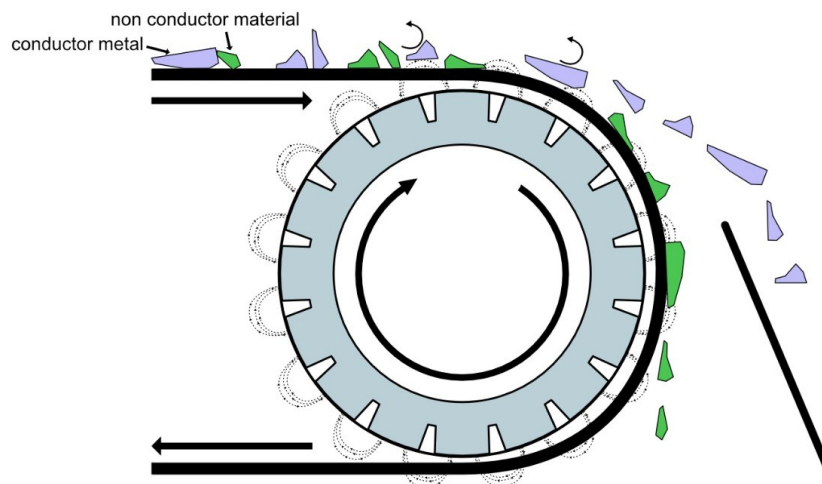


Figure 7: Working principle of ECS. (Adapted from Rao, 2007).

The deflection of the metals depends upon the electrical conductivity and density as well. Table 6 shows the deflection co-efficients of different materials based on electrical

conductivity and density. Where σ represents the electrical conductivity in $10^6 \text{ m}^2/\Omega\text{m}$ and ρ represents density in 10^3 Kg/m^3 .

Table 6: Deflection coefficients of metals and materials (Adapted from Yazici et al., 2010).

Material/Metal	Electrical conductivity/Density (σ/ρ) $10^3 \text{ m}^2/\Omega.\text{Kg}$
Aluminum (Al)	13.0
Copper (Cu)	6.7
Silver (Ag)	6.0
Zinc (Zn)	2.4
Gold (Au)	2.1
Tin (Sn)	1.2
Iron (Fe)	1.2
Lead (Pb)	0.45
Glass	0.0
Plastics	0.0

According to (Hadi et al., 2015) the non-metallic fraction from WEEE PCBs is used for phenolic molding, as a construction industry filler, a polymer composite filler, for production of porous material and for adsorbent production.

2.5.4.1: Limitations of ECS: The separation gets inefficient with the lower particle size ranges. The separation recovery of particles below 5mm decreases. The separation also depends on the shape of the particles.

In case of WEEE, metals are not well liberated unless comminuted below 1mm. This makes them less accessible (Hubau et al., 2019). If the material is comminuted below $63 \mu\text{m}$, then there is an increase in the loss of those fines (Hubau et al., 2019).

3. Research Process/Methodology:

The research was carried out with ECS and OS with an aim to compare them for the separation efficiency of the mixed residue of WEEE. The tests for optical sorting will be conducted at Spectra media while the experiments for ECS will be done at the Laboratory for mineral processing and environment protection of Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb. Results of both the experiments were analyzed to make a comparison and draw conclusions. The feed sample was sorted manually to analyze it for the composition of it. This helped to know the feed sample and thus use that information for the calculations at a later stage.

3.1: Sample Preparation:

The company Spectra media collects the WEEE from all over the country. They have created several collection points. Also, the residents can order a pickup of WEEE with appointments made online. The waste is collected and sorted in 6 different categories which is also directed by the EU WEEE Directive 2019.

- 1: Heat Exchange equipments: These include refrigerators, freezers, air conditioners and heat pumps
- 2: Equipments having screens greater than 100cm²: Screens, monitors, televisions fall under this category.
- 3: Bulbs/Lamps: Fluorescent lamps, LEDs, sodium lamps.
- 4: Large Equipments: This category contains washing machines, tumble dryers, dishwashers, electric stoves, photocopying equipments, photo-voltaic panels.
- 5: Small Equipments: Vacuum cleaners, microwaves, sewing machines, electric kettles, coffee machines, hair and body care devices etc.
- 6: Small IT equipments: Mobiles, laptops, printers, GPS devices, calculators, routers.

Spectra media has an installed capacity of 4000 Kg/h and it processes about 20,000 t of WEEE annually.

Spectra media receives the input material at the parent company in Virovitica.

Preliminary sorting of the waste is done and then the material is subjected to crushing with a hammer mill. They also use a chain crusher to break/open the casings of the material to avoid unnecessary crushing of the valuable materials inside. This is done for example for WiFi routers, CD and DVD ROMs.

A coarse magnetic separator removes the iron fraction of this crushed material. Then manual look and pick method is employed to remove motors, transformers, batteries, rubber, PCBs etc. The rest of the material is then subjected to crushing again.

This pre-sorted and crushed material is transported to Spectra Media located in Donja Bistra.

The input material is then shredded with a primary knife shredder. This comminutes the material to 80 mm. After this the material undergoes magnetic separation which removes the iron fraction from the stream. The remaining material is transported with a conveyor belt where the employees hand-pick the hazardous material like batteries, capacitors, PCBs, transformers and electric motors. And these employees put the picked material in the designated bins. The material on the conveyor belt is sent to the secondary shredder which is also a knife shredder. This shredder reduces the size of the material to 20 mm. The material then goes through the magnetic separation unit where remaining iron is removed from it. There is also a Neodymium magnet which removes any remaining ferrous particles from the material. All the iron removed from the stream is sent to the partner smelter. The rest of the material passes through an eddy current separator where Aluminum and light metals are separated. The remaining material then passes through a drum screen where the oversize fraction is sent back to the secondary shredder. The rest of the material goes through the zigzag separator which is an air classifier. This zigzag separator removes the light plastic fraction from the material stream which includes foils, sponges, gums and plastics. The light plastic fraction is sent to landfills. The heavy fraction from the zigzag separator is sent to the optical separator. **This heavy fraction was the feed for both optical sorting process and eddy current separation process in this research. (You made it bold, should I remove it?).**

The heavy fraction separated from the zigzag classifier is weighed and is fed into the optical sorting machine through the feed hopper. The material is conveyed by a conveyor belt while a vibrator is used to make a mono layer of the material on the belt. The formation of a single layer of material is very important in optical sorting so that all the particles get an equal chance to be detected by the sensor and camera. The material then passes through the sensor which allocates the material to either reject or accept bins. Air jets are used to then direct the material into the designated bins.

Fig 8 shows the process flow sheet of the separation process at Spectra media, it also shows sample preparation in this research.

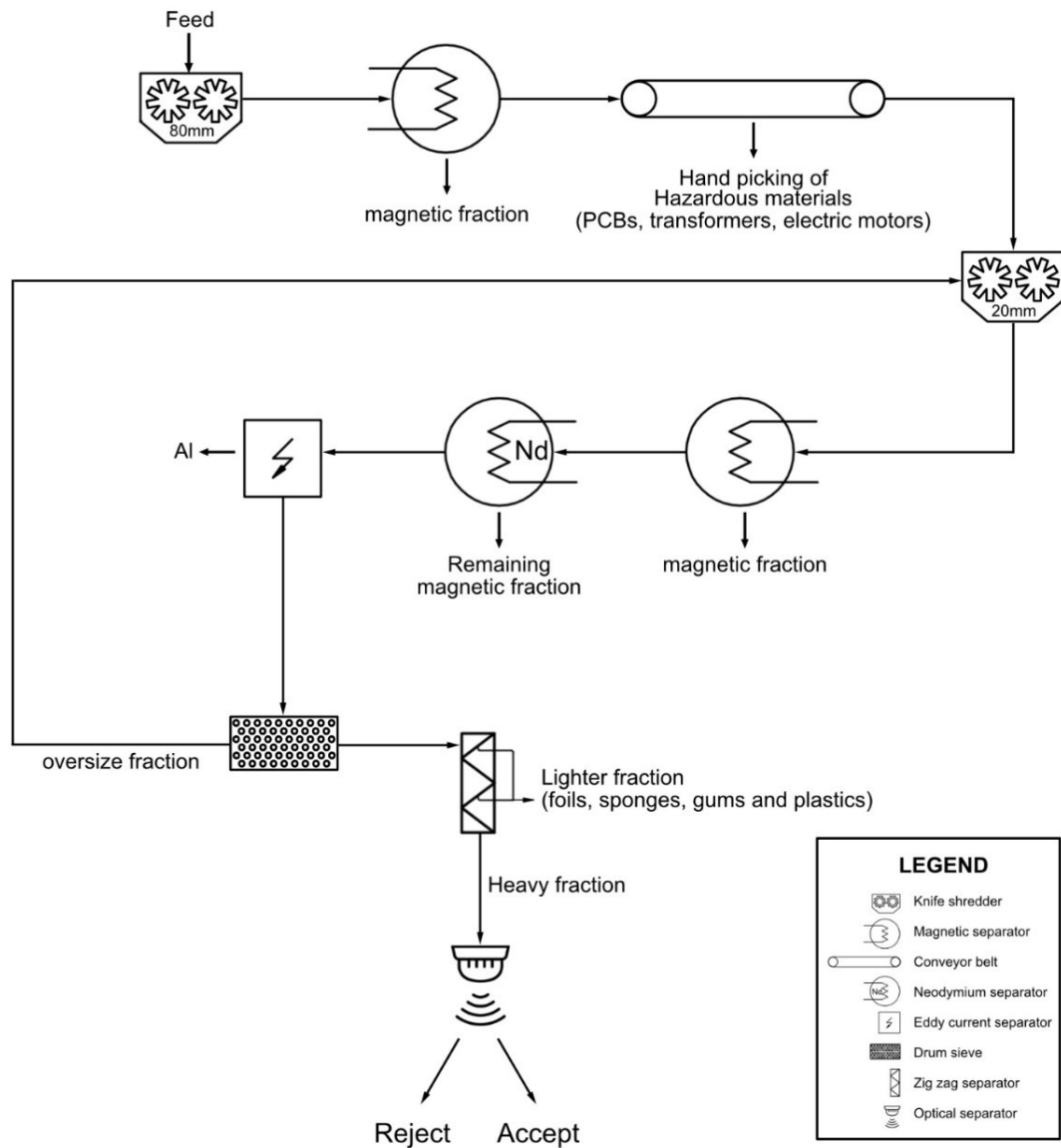


Figure 8: Process flow at Spectra media / sample preparation process.

3.2: Analysis of Feed Sample Composition:

At Spectra media three grab samples were taken from the heavy fraction separated by the zig-zag separator. Samples were taken from the material which was sent to the optical separator for analysis. So that the feed for both the processes to be tested is the same.

The material was sorted manually by look and pick method into seven different fractions. The material contained plastics, glass, stones, aluminum, copper/brass, wires and composite material. Figure 9 shows the material fractions after the manual sorting of the sample was done. Table 7 shows the composition and weight percentages of the samples analyzed by manual sorting. It was seen that the highest percentage was of stones and glass in all the feed samples followed by aluminum, plastics, composite material, Cu/Brass and wires respectively. Composite material contained wires with insulations,

parts of printed circuit board parts or any other material where two or more materials were joined together.



Figure 9: Individual material fractions contained in the feed sample.

Table 7: Average composition and weight percentages after manual sorting of feed samples.

	Sampl e 1 (g)	Weigh t %	Sampl e 2 (g)	Weigh t %	Sampl e 3 (g)	Weigh t %	Averag e (g)	Weigh t %
Plastics	245.38	10.79	183.54	8.80	201,8	9.52	210.24	9.74
Cu/Brass	93.08	4.09	97.09	4.65	87,9	4.15	92.69	4.29
Aluminu m	272.68	11.99	297.52	14.26	291,01	13.73	287.07	13.29
Stone	828.02	36.42	701.34	33.62	764,5	36.08	764.62	35.41
Glass	574.6	25.27	558.59	26.78	554,67	26.18	562.62	26.05
Wires	70.34	3.09	104.4	5.00	54,6	2.58	76.45	3.54
Composit e	189.64	8.34	143.59	6.88	164,2	7.75	165.81	7.68
Total	2273.7 4	100	2086.0 7	100	2118,6 8	100	2159.5	100

Fig 10 gives us a comparison of the material composition in our feed samples. The samples are shown on x-axis while y-axis shows the mass of materials in grams. Every single material is shown with a different color. Whereas Fig 11 shows the average composition of the feed sample. The highest percentage in the sample is of stones and glass. This average feed sample is used for testing with ECS process.

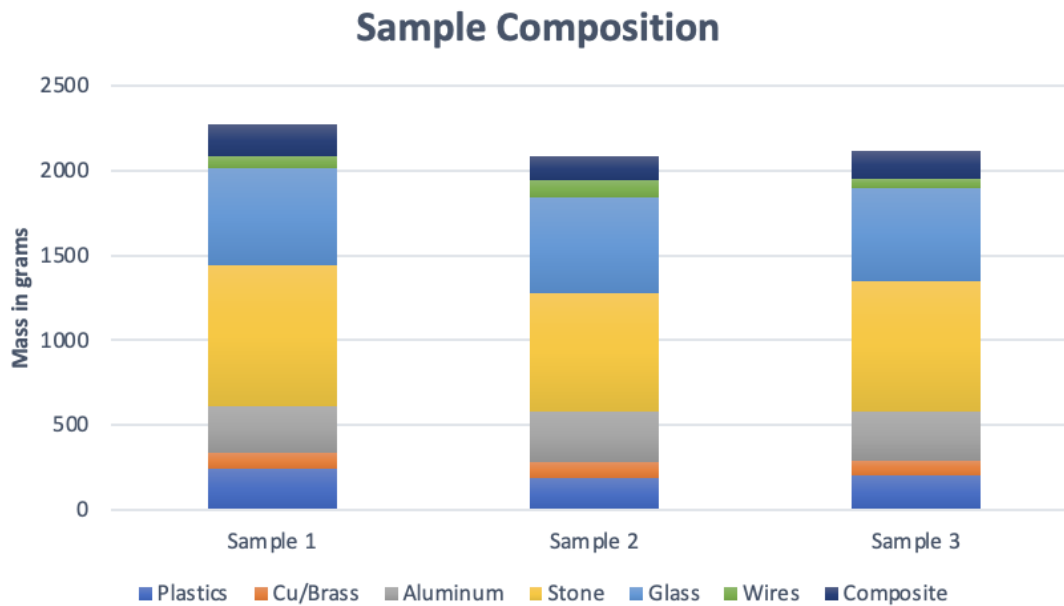


Figure 10: Material composition comparison of the feed samples.

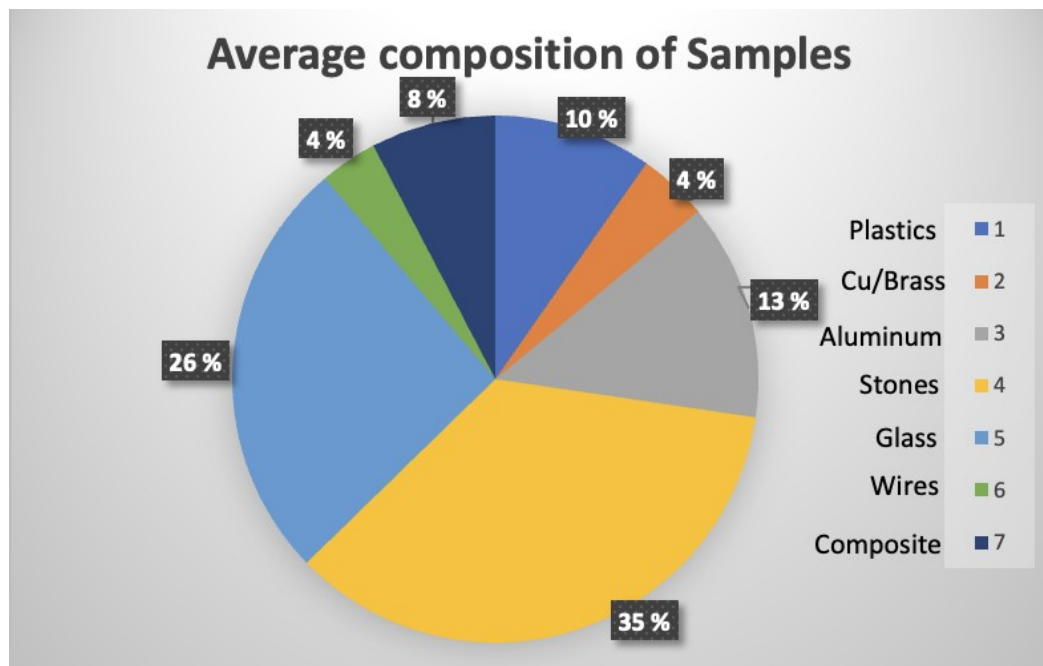


Figure 11: Composition of feed samples.

3.3: Optical Separation:

The heavy fraction from the zig-zag separator was collected in the bin. This test sample was loaded into the hopper after weighing it. From the hopper, the material was transported through a conveyor belt. A vibrator equipped on the stream distributes the material over the conveyor belt in a single layer. This makes sure that all the particles have an equal opportunity of recognition by the light source and thus to end up in the right bin. The optical sorting separator works with selecting the separation function based on color, shape and transparency or reflective properties of the material to be separated. For

separating the material based on a specific property, the desired parameters are set. For wires, selection based on the shape of the material is selected and the material is allowed to pass through the light source. Upon classification of the material as wires, the air jets eject the wires to the concentrate or accept bin while the rest of the material falls into the tailings or reject bin. To separate the wires efficiently, the reject material was sorted again with optical sorting so that the remaining wires could be recovered. The wires were sorted twice.

After separating the wires successfully, the program was set to separate glass from the feed material. To separate glass, separation criterion based on the transparency and reflectivity is selected. As soon as the material is identified as glass, the air jets eject those particles from the material stream and direct them to the concentrate while the rest of the material goes to tailings bin.

Next, the program was set to separate aluminum from the remaining. For aluminum, separation based on color is chosen. In optical sorting aluminum is sorted based on its grey color. So, all the greyish stones, ceramics and plastic material were also sorted into the accept bin carrying aluminum.

After that, the material was fed again to the optical sorter, this time to separate Cu/Brass from the rest. Cu is also separated based on its color.

1017 kg of material was sorted by optical separator. The final separation results of optical sorting are presented in the table 8. However, the feed sample is shown in the figure 12.



Figure 12: Feed sample for optical sorting process at spectra media.

Table 8: Weight percentages of Optical sorting products.

Material	Weight	
	(kg)	(%)
Wires	64	6.29
Glass	242	23.80
Al, stones, ceramics, plastic	557	54.77
Cu & brass	40	3.93
Final reject	101	9.93
Losses (dust)	13	1.28
Sample weight	1017	100.00

3.4: Eddy Current Separator:

The ECS available in the Faculty of Mining, Geology and Petroleum Engineering is a MagnaPower 300 model.

There are three working parameters which govern the separation process in an ECS.

1. Belt speed: The belt speed is given in Hertz (Hz) and is shown on the dials. It can be adjusted from 25 Hz to 50 Hz. 25 Hz corresponds to a value of 1.32 m/s while 50 Hz corresponds to 2.67 m/s.
2. Splitter position: Splitter position also plays an important role in the separation process by ECS. The splitter position can be adjusted between -5 and 4. At position -5, the splitter is most distant and farthest away from the belt. While position 4 is the closest to the belt.
3. Rotor Speed: The separation process is also affected by the speed of the internal magnetic rotor. The rotor speed can be adjusted till 100 Hz, but it is recommended by the supplier to run it at 70% of the maximum speed.

These three working parameters (independent variables) are shown in the Fig 13.

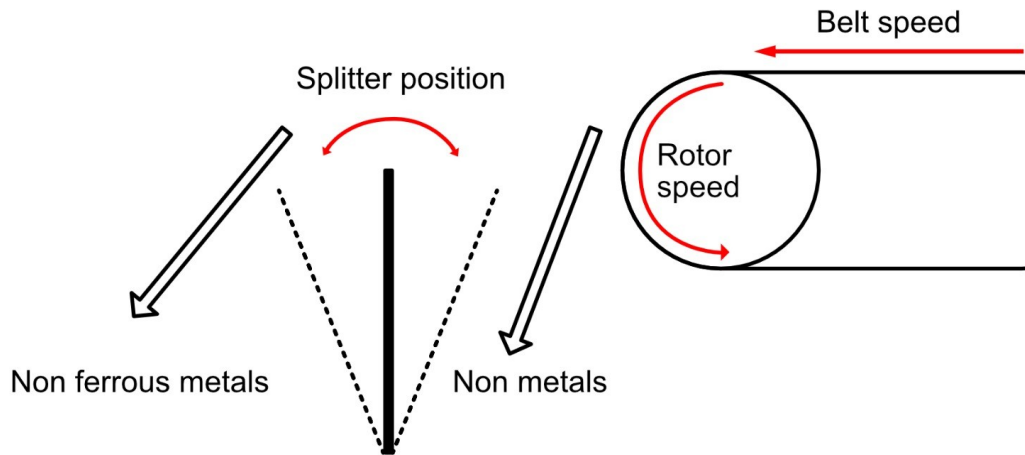


Figure 13: Independent variables for the ECS process (Adapted from MAGNAPower 2020).

3.4.1: Test Design:

To design a test plan for ECS, manually sorted material was preliminarily tested. This was done to understand the characteristics of the feed material like their deflection susceptibility and to optimize the working parameters of ECS.

Initially the belt speed was set to be 35 Hz, the splitter position was adjusted to 2.5 while the rotor was kept off. In this case most of the stones, glass and the plastics were collected in the concentrate bin. The belt speed was then changed to 38.5 Hz. Also, the splitter position was set to 2. Some fraction of stones, glass and plastics was found in the concentrate (non-ferrous fraction, fig. 13) while most of it was collected in the tailings (non-metals fraction, fig. 13) bin.

Now the splitter position was changed to 1.5. For the stones fraction, there was no stone in the concentrate. For glass, only one glass particle moved to the concentrate bin. And for plastics, two particles were found in the concentrate bin.

For testing the metallic fractions, the magnetic rotor was turned on and the rotor speed was set to 70 Hz. While the splitter position and belt speed were maintained at 38.5 Hz and 1.5 respectively.

In case of aluminum, most of the aluminum was collected in the concentrate bin. In case of wires, about 60% were collected in the tailings bin and 40% in the concentrate. While in case of Cu/brass, about 55% was collected in the concentrate and 45% was in tailings bin. On the other hand, for composite material, about 65% material got collected in the concentrate and 35% in the tailings.

So, the better performing parameters for ECS were adjusted by the preliminary testing and are shown in the table 9. These are also considered to be the nominal or “central values” in Central Composite Design for the succeeding test work.

Table 9: Optimum conditions for the preliminary test work using ECS.

Splitter position	1.5	
Belt speed	38.5	Hz
Rotor Speed	70	Hz

For the test work with ECS, Central Composite Design (CCD) was chosen for designing the experiments (DOE). With DOE, the intention was to observe the behavior of the system with minimum number of experiments. It allowed to understand how the independent variables (ECS working parameters) are affecting the process and which variable has more impact on the process. In this design, belt speed, splitter position and the internal rotor speed are the independent variables affecting the process. While grade and recovery of the metals (Aluminum and Copper) are the dependent variables. With central composite design, 17 test points were designed.

The coded values are translated into the corresponding real values using the following formula:

$$X=C*X_0+X_0$$

Where C denotes the step change and X is the coded value while X_0 is the central value for the variable. The step for belt speed, splitter position and rotor speed were chosen to be 5Hz, 1.5 and 10Hz respectively.

Using this formula, the real values were found out for all the working parameters (independent variables) and are given in the table 10. The coded values are shown in bold.

Table 10: Coded and real values of the independent variables.

Independent variable	Coded values				
	-1.6732	-1	0	1	1.6732
Belt speed (Hz)	30	33.5	38.5	43.5	47
Splitter position	-1	0	1.5	3	4
Rotor speed (Hz)	53	60	70	80	87

Thus, with these coded and the corresponding real values, 17 test runs were designed using the software Statistica. Table 11 shows the coded and real values for all the tests to be performed. The tests 5,10 and 17 are denoted with C because they represent the center test points.

Table 11: Test plan for ECS using DoE.

Run	Coded Values			Real Values		
	Belt Speed	Splitter position	Rotor speed	Belt Speed (Hz)	Splitter position	Rotor speed (Hz)
1	-1	-1	-1	33.5	0	60
2	-1	1	1	33.5	3	80
3	1	-1	1	43.5	0	80
4	1	1	-1	43.5	3	60
5 C	0	0	0	38.5	1.5	70
6	-1	-1	1	33.5	0	80
7	-1	1	-1	33.5	3	60
8	1	-1	-1	43.5	0	60
9	1	1	1	43.5	3	80
10 C	0	0	0	38.5	1.5	70
11	-1.6732	0	0	30.0	1.5	70
12	1.6732	0	0	47.0	1.5	70
13	0	-1.6732	0	38.5	-1	70
14	0	1.6732	0	38.5	4	70
15	0	0	-1.6732	38.5	1.5	53
16	0	0	1.6732	38.5	1.5	87
17 C	0	0	0	38.5	1.5	70

The initial samples which were manually sorted, were homogenized to make six identical samples. These samples were then used to perform the tests as designed by DoE.

The sample was tested with ECS by setting the corresponding real values of the independent variables. After the test, the material was collected in two bin, namely concentrate and tailings. Both concentrate and tailings were analyzed for the individual products by sorting them manually. Figure 14 shows the individual products after ECS in

concentrate while figure 15 shows the tailings. Run 7 is shown here as an example to show how ECS has performed. The individual products are plastics, aluminum, Cu/Brass, glass, stone, wires and composite material. This procedure was done for all the 17 test runs.

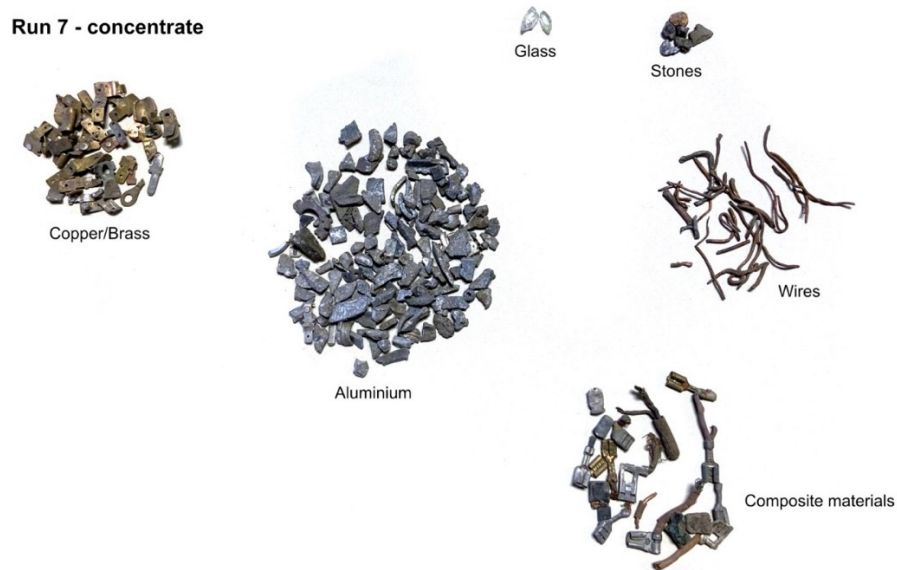


Figure 14: Composition of ECS concentrate from Run 7



Figure 15: Composition of ECS tailings from Run 7

3.5: Sieve analysis:

Sieve analysis of the feed samples was also done to know about the particle size distribution of the material. It helped to see how material was distributed over different size classes. With cumulative retained material, D80 was calculated, which gives the size of the particles at which 80% of the material is retained on the sieve. Otherwise, D20 for passing would give the size of the particles at which 20% material passes the sieve. D80 from cumulative retained and D20 from cumulative passing would give the same value.

4: Results and Discussions:

In this section, the results of both the optical separation and ECS will be discussed. The results were analyzed to compare both the processes based on their separation efficiency. This analysis was used to draw conclusions from this study.

4.1: Sieve Analysis:

Sieve analysis of the individual samples was also done to analyze the grain size. As the material being sorted was quite coarse thus the sieves from 10 mm to 2 mm were selected for the sieve analysis. To make sure that all the particles had the chance to go through a sieve, the sieve was shaken horizontally, vertically, and around the axis. This allowed the particles of different shapes to orient themselves along the mesh and thus pass through. Table 12 shows the sieve analysis result of the average feed sample. About 62% material falls in the size range from 4 mm to 8 mm.

Table 12: Sieve analysis for the average Feed sample.

Grain size (mm)	Weight (g)	Weight %	Cumulative retained (g)	Retained %	Cumulative passing (g)	Pass %
+10	123.71	12.40	123.71	12.40	874.14	87.60
10 / 8	178.59	17.90	302.30	30.29	695.55	69.71
8 / 4	621.62	62.30	923.92	92.59	73.92	7.41
4 / 2	63.12	6.33	987.04	98.92	10.80	1.08
-2	10.80	1.08	997.84	100.00		0.00
Total	997.84	100.00				

Figure 16 shows the graphs for cumulative retained and passing percentages for the average feed sample. D80 from the cumulative retained percentage is calculated while D20 from cumulative passing percentage is calculated. The value for both D80 or D20 was 4.8 mm.

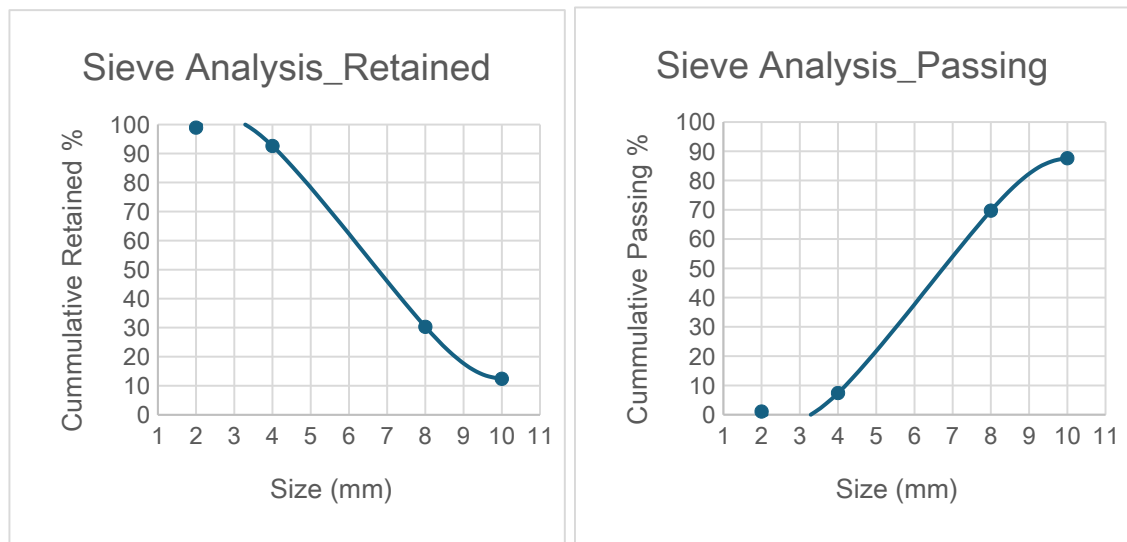


Figure 16: Cumulative retained and passing percentages of average feed sample.

4.2: Optical sorting results:

Initially 1017 Kg of material was processed using optical separator. But with that it was not possible to calculate grade and recovery of the individual materials. Only mass recoveries could be calculated. Because it was not possible to sort this much of the material manually.

So, to be able to do a fair comparison with the ECS process, the same feed sample from ECS was used to test with optical sorting process at Spectra media. In the first stage, wires were collected in the concentrate (fig. 18a). Wires were sorted based on their shape. The tailings were fed to the optical separator again and the selection function for glass based on its transparency was chosen. This time concentrate contained most of the glass and very little amounts of the other fractions (fig. 18b). The tailings from this stage were then used to separate Al. Al was separated based on its color. With Al in the concentrate, a lot of stones were also collected in the concentrate because of the similar color (fig. 19). All the grayish material was collected with Al. Another stage was run for collecting Cu/Brass based on color as well. The Cu/Brass concentrate contained a lot of stones and some plastics having similar color (fig. 20). The flowsheet of the whole optical separation process at Spectra media is shown in Fig 17. The tailings from each subsequent stage were fed to the optical separator again to process it for the desired product in the concentrate.

Optical Separator Flowsheet

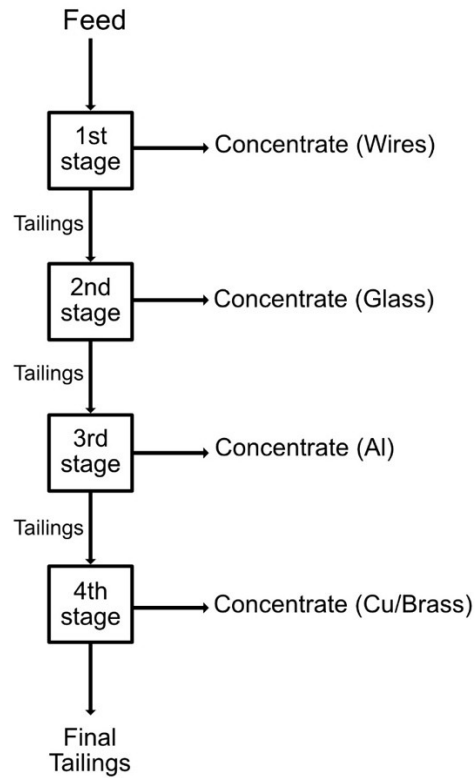


Figure 17: Flowsheet of Optical sorting process at Spectra media.

The separation results are shown in the following table 13. This table shows the weights and weight percentages of each concentrate after every separation stage. The tailings from each stage were re-processed again with the optical separator to get the next concentrate.

Table 13: Weights of the concentrates separated by optical sorting at Spectra media.

		Weight (g)	Weight %
Stage 1	Wires Concentrate	599.31	10.02
Stage 2	Glass Concentrate	1391.17	23.27
Stage 3	Al Concentrate	2480.1	41.48
Stage 4	Cu/Brass Concentrate	168.43	2.82
	Reject	1339.52	22.41
	Total	5978.53	100.00

As these concentrates (table 13) contained gangue material as well, so these concentrates were sorted manually to obtain the purer fraction of the desired material in each

concentrate. This allowed calculation of the grade and recovery of each material in respective concentrate and tailings. These values are shown in table 14. This table shows the grade and recovery of Al, Cu/Brass, Wires and Glass separated by optical sorting process. 83% of wires were collected in the first stage of optical separation with a grade of 29.6%. In 2nd stage, about 84% of glass was recovered in the concentrate at a grade of 93%. 87% Al was recovered in the 3rd stage with a grade of around 25%. While in last stage approximately 24% of Cu/Brass was collected in concentrate with a grade of about 22%.

Table 14: Grade and Recovery of individual materials in different stages of OS.

	Feed		Concentrate		Tailings		Recovery %	Stage
	Weight (g)	Grade %	Weight (g)	Grade %	Weight (g)	Grade %		
Wires	211.74	3.54	177.53	29.62	34.21	0.64	83.85	1
Glass	1534.97	28.54	1296.68	93.21	238.29	5.98	84.48	2
Al	704.61	17.67	617.78	24.91	86.83	5.76	87.68	3
Cu/Brass	154.14	10.22	36.80	21.85	117.34	8.76	23.87	4

The wires concentrate and glass concentrate are shown in the Fig 18 below. Wires are shown in the left side of the figure (a) while glass concentrate on the right side (b). It can be seen in the figure 18 (a) that the wires concentrate contained Cu/Brass particles, some aluminum and composite material as well. The concentrate also contained all the wires with insulations which otherwise should have been sorted as composite material. This is because of the selection function for wires, as wires are separated based on their shape in the optical separator.

For glass, the optical separator did a very good job. Most of the glass (85%) was collected in the glass concentrate at a high grade of 93%. Glass was separated based on its transparency. However, some of the colored glass was not identified as glass and it ended up in other concentrates. The glass concentrates also contained some percentage of all the other materials.

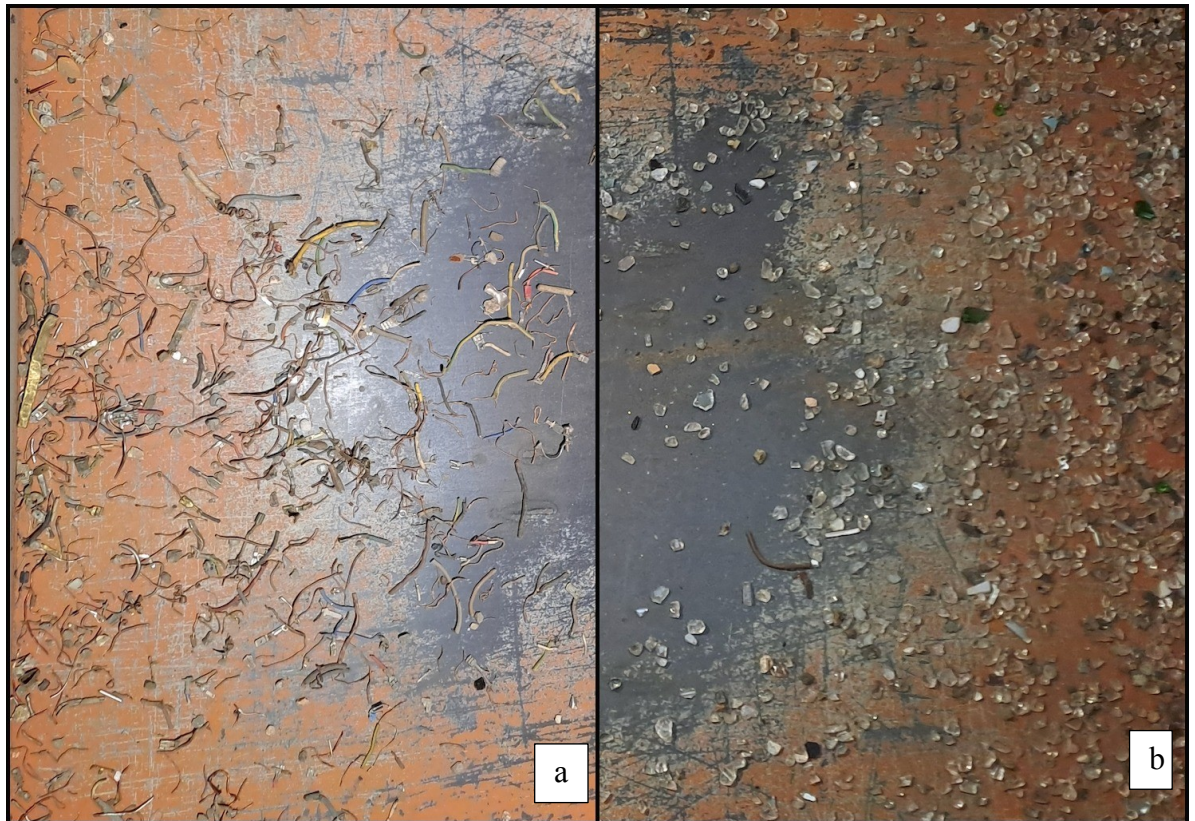


Figure 18: Wires concentrate (a) and glass concentrate (b) from optical separator at Spectra Media.

For aluminum, the selection function based on its grey color was chosen. And as the feed material contained a lot of grayish stones and composite material, all of those showed up in the aluminum concentrate. This can be seen in the Fig 19. As the feed material contained around 35% stones and most of them were grayish so because of the chosen selection function they all showed up in the concentrate rather than being ending in the tailings. Thus, in case of optical separator the quality of the concentrate is not high. The grade of aluminum in the concentrate was about 25% with a recovery of around 87%.



Figure 19: Aluminum concentrate from Optical separator at Spectra Media.

For Cu/Brass concentrate, the selection function was also color based. In this case all the particles having color like Cu/Brass showed up in the concentrate. So, all the yellowish/orangish particles ended up in the concentrate with Cu and brass. This can be seen in the Fig 20. Some stone particles can be seen in the concentrate which had color similar to the Cu/Brass particles.



Figure 20: Cu/Brass Concentrate from optical separator at Spectra Media.

4.3: ECS Results:

As discussed in the previous chapter, a Central Composite Design was chosen for the test work. All the 17 tests were conducted on the individual samples and were sorted accordingly to make a comparison of concentrate and tailings. For all these 17 test runs, the feed samples were identical in composition.

Recovery and grade of the metals (Aluminum and Copper/Brass) were also calculated for all the test runs. Al and Cu/Brass were considered to be one element for all the calculations. The grade and recovery values are for Al and Cu/Brass together and not for one of them. The tests were compared to see how the recovery and grade changes with the changes in device working parameters/independent variables (belt speed, splitter position and rotor speed). Table 15 gives an insight into the grade and recovery of the metals for each test run. Test Run no. 5, 10 and 17 were shown in bold as they represent the center test points. In the center test points, the values of all the independent variables were set to zero as coded value.

The results for these center points are comparable as the independent variables are set to the same values. The variations are due to the differences in the grain size and shape of the feed.

For certain test runs, the grade was quite high, but the corresponding recovery was too low and vice versa. In some test runs, the grade and recovery both were average.

For example, test run 1 yielded a grade of 92% for metals but a recovery of only 4%. Similarly, test run 9 yielded a recovery of 89% but at the same time the grade fell below 19%. Thus, a trade-off must be chosen between grade and recovery.

Table 15: Grade and recovery for all the 17 test runs after ECS.

Run nr.	Feed		Concentrate				Tailings			Grade	Recovery
	Al + Cu	Other Mat	Total	Al + Cu		Other Mat	Al + Cu		Other Mat	(of conc)	(in conc)
	%	%	g	g	%	%	g	%	%	(%)	(%)
1	17.59	82.41	7.27	6.67	91.75	8.25	0.60	17.16	82.84	91.75	3.79
2	17.59	82.41	180.51	117.02	64.83	35.17	63.49	7.19	92.81	64.83	66.55
3	17.59	82.41	133.18	92.82	69.70	30.30	40.36	9.59	90.41	69.70	52.78
4	17.59	82.41	842.88	148.77	17.65	82.35	694.11	17.66	82.34	17.65	84.60
5	17.59	82.41	172.93	113.88	65.85	34.15	59.05	7.58	92.42	65.85	64.76
6	17.59	82.41	22.70	21.84	96.21	3.79	0.86	15.94	84.06	96.21	12.42
7	17.59	82.41	146.68	110.43	75.29	24.71	36.25	7.59	92.41	75.29	62.80
8	17.59	82.41	104.50	86.82	83.08	16.92	17.68	9.84	90.16	83.08	49.37
9	17.59	82.41	838.49	156.78	18.70	81.30	681.71	10.95	89.05	18.70	89.16
10	17.59	82.41	162.77	110.78	68.06	31.94	51.99	7.72	92.28	68.06	63.00
11	17.59	82.41	22.45	19.76	88.02	11.98	2.69	15.97	84.03	88.02	11.24
12	17.59	82.41	840.73	154.50	18.38	81.62	686.23	13.37	86.63	18.38	87.86
13	17.59	82.41	18.82	18.82	100.00	0.00	0.00	15.98	84.02	100.00	10.70

14	17.5 9	82.4 1	827.8 8	155.4 2	18.77	81.2 3	672.4 6	11.7 9	88.2 1	18.77	88.38
15	17.5 9	82.4 1	150.9 7	106.2 3	70.36	29.6 4	44.74	8.17	91.8 3	70.36	60.41
16	17.5 9	82.4 1	179.5 0	113.4 1	63.18	36.8 2	66.09	7.59	92.4 1	63.18	64.49
17	17.5 9	82.4 1	189.3 3	114.8 7	60.67	39.3 3	74.46	7.51	92.4 9	60.67	65.32

4.4: Grade-Recovery Curve:

A grade-recovery curve was plotted to see the relationship between them. It does not look exactly like the typical grade-recovery curve for an ore because of the grain size and the amount of liberation of metals in the waste stream. The tests here were performed on a rather coarser material where D80 was around 4.8mm. The variations in the grade and recovery are associated with the coarser grain size and the shape (every grain has unique shape). However, the general trend shows that as the grade increases the recovery decreases and vice versa. The relationship is shown graphically in the Fig 21.

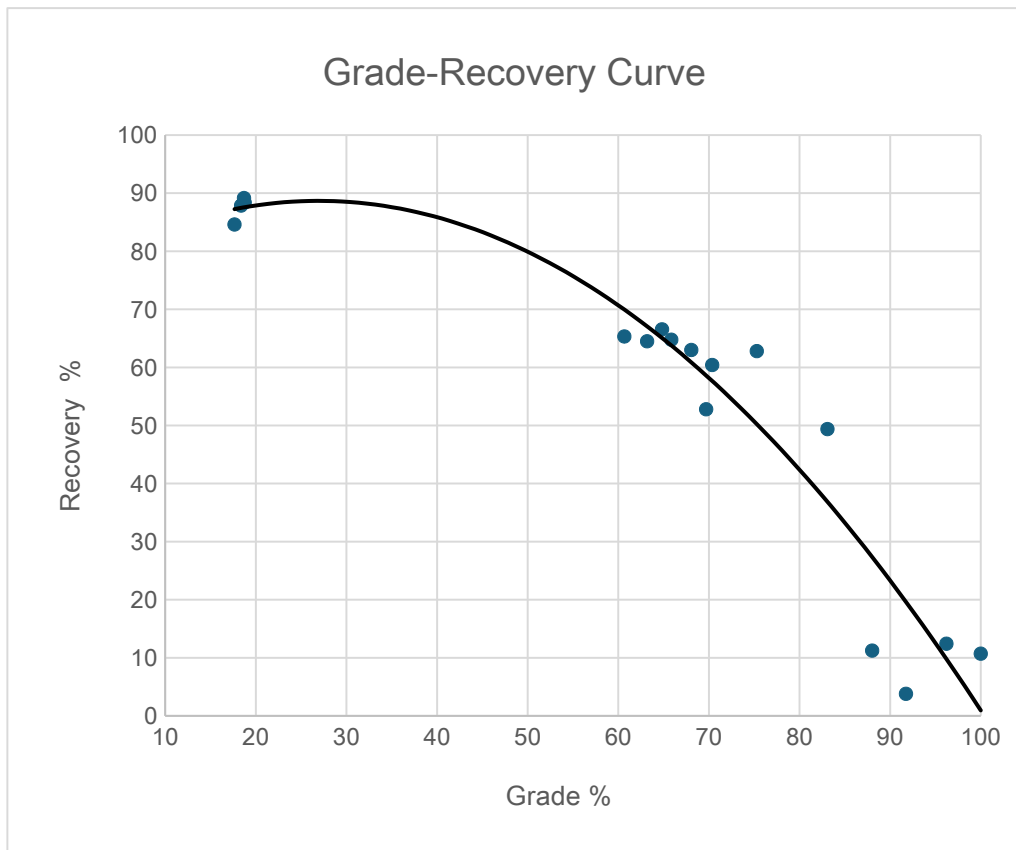


Figure 21: Grade-Recovery curve for the metals (Al and Cu/Brass).

4.4.1: Relationship of Recovery to the independent variables:

Recovery of metals changed with a change in the independent variables. The recovery values for each run were observed to find out which independent variable had the most impact on it. Fitted surface in Fig 22 shows the change in recovery with the change in the rotor speed and belt speed. In this case the third variable splitter position has a coded value of zero or a real value of 1.5. With an increase in the belt speed, the recovery increases but as the rotor speed increases, the recovery does not increase. Rotor speed has a negligible effect on the recovery.

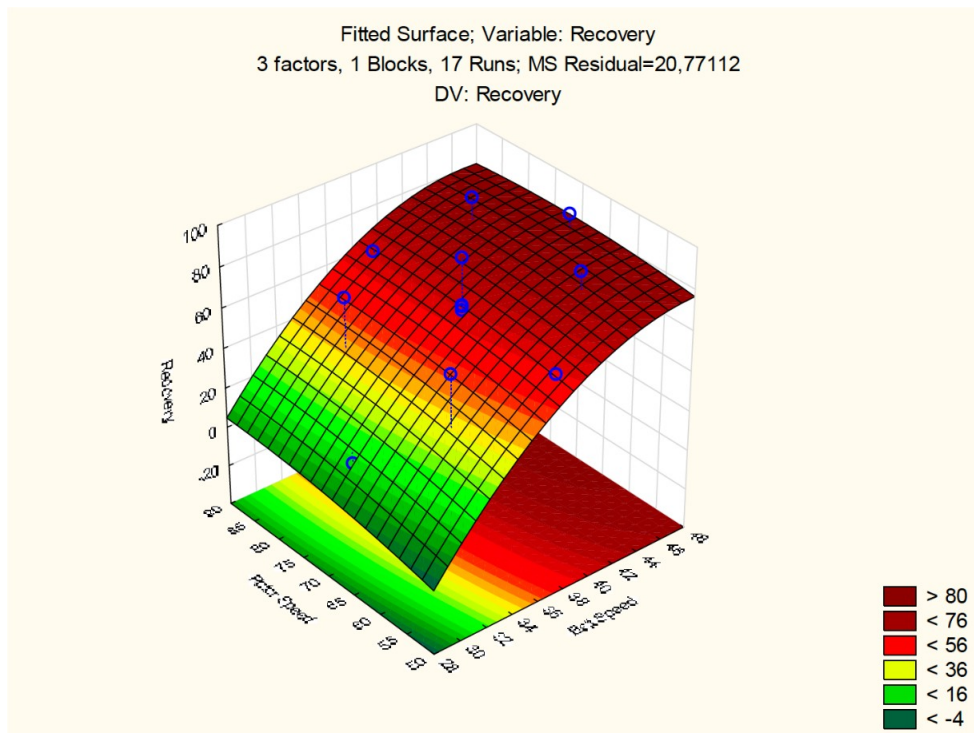


Figure 22: Fitted surface of recovery with rotor speed and belt speed.

Similarly, the relationship is studied for the variation in recovery because of changes in the rotor speed and the splitter position. Fig 23 shows the fitted surface for recovery when observed against rotor speed and splitter position. In this figure the belt speed is set at coded value of zero or the real value of 38.5Hz. Recovery increases with the increase in splitter position from the negative value to the positive value and vice versa. However, a higher rotor speed does not impact the recovery.

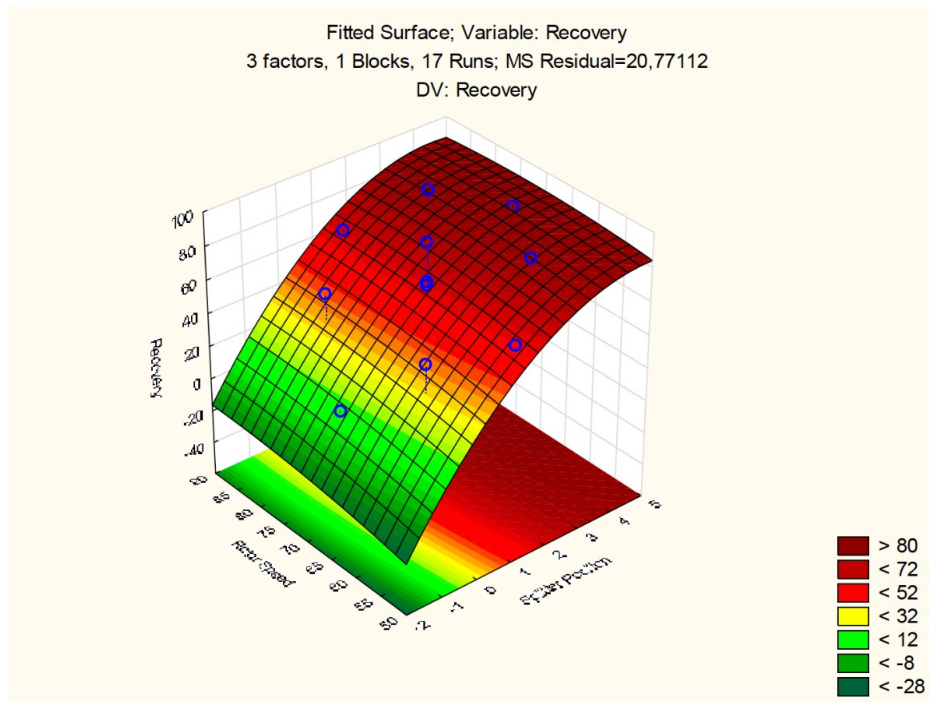


Figure 23: Fitted surface of recovery with rotor speed and splitter position.

The changes in recovery observed against the splitter position and the belt speed are shown in Fig 24. Here the rotor speed is at the coded value of zero or real value of 70Hz. The recovery increases with a higher belt speed and an increase in splitter position from negative to a positive value and vice versa.

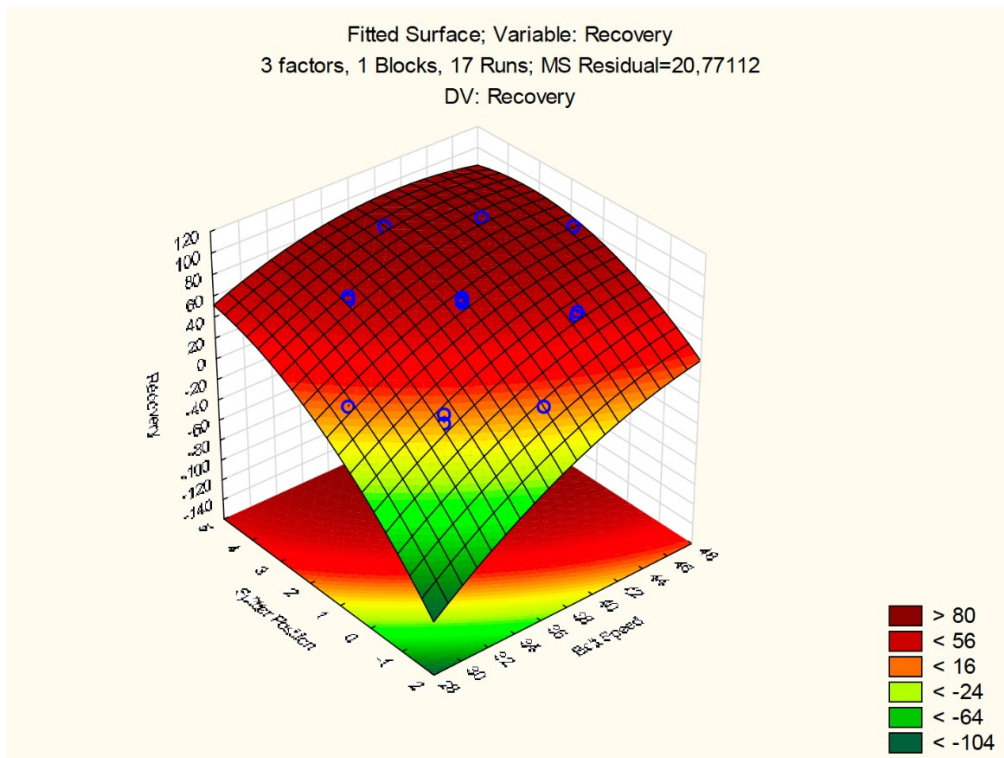


Figure 24: Fitted surface for recovery against the splitter position and belt speed.

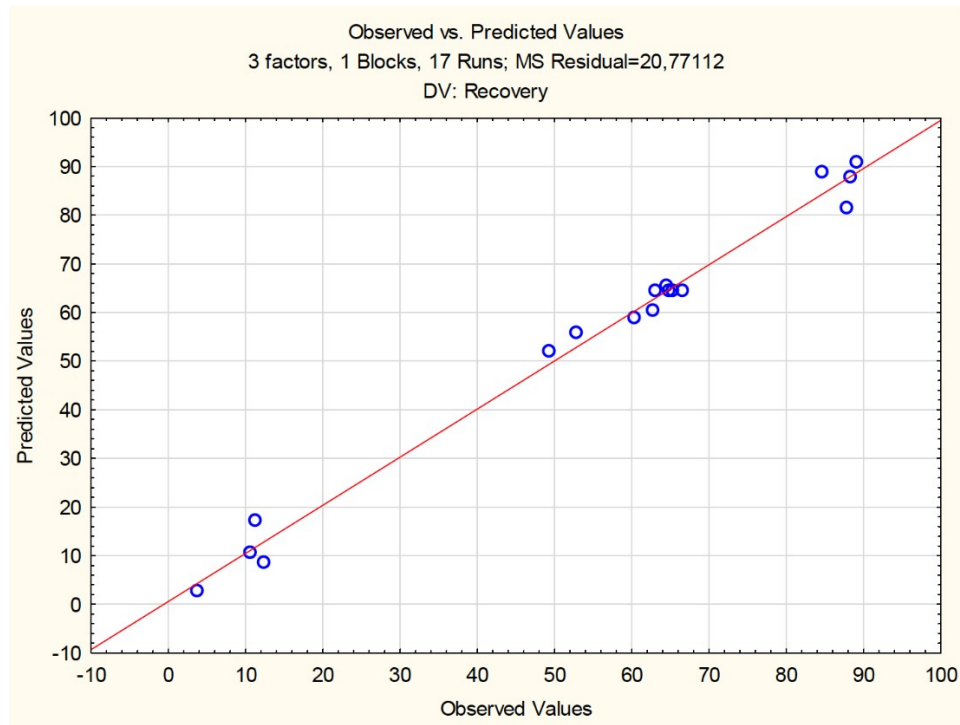


Figure 25: Observed and predicted values for recovery.

Fig 25 shows the relationship of the 17 observed values with the values predicted by the program Statistica. Observed values are shown on the x-axis while y-axis shows the predicted values. The blue dots show the 17 tests done with ECS.

Recovery Model:

The model equation for recovery is given as follows.

$$Y = -545.67 + 21.73x_1 + 51.56x_1^2 + 1.76x_2 - 0.21x_2^2 - 2.43x_3 - 0.008x_3^2 - 0.69x_1x_2 - 0.01x_1x_3 - 0.03x_2x_3$$

It can be seen from the model equation as well that the variables x_1 and x_2 had higher impact on the recovery of metals. x_1 is belt speed while x_2 is the splitter position. While the independent variable x_3 (rotor speed) had a negligible impact on the recovery of metal.

4.4.2: Relationship of grade with the independent variables:

The behavior of grade change was studied in relation to the independent variables. With the change in splitter position, belt speed and rotor speed, grade changed. Fig 26 shows the fitted surface showing the relation of grade with the change in rotor speed and belt

speed. The grade increases at lower belt speeds and decreases at higher belt speed. However, changing the rotor speed does not influence the grade much. In this case the third variable (splitter position) is kept at a coded value of zero.

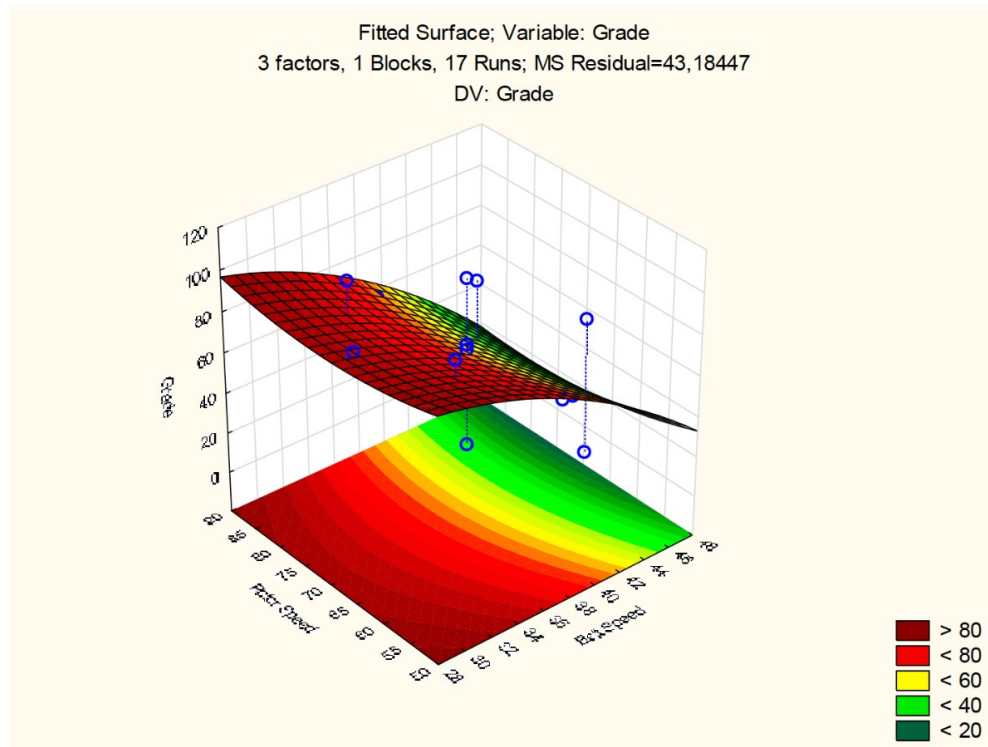


Figure 26: Relationship of grade with rotor speed and belt speed.

Likewise, the fitted surface of grade against rotor speed and splitter position is seen in Fig 27. The grade decreases by moving the splitter position from negative to the positive values and vice versa. While the rotor speed does not have a significant influence on the grade. Belt speed is set to coded value of zero or a real value of 38.5 Hz.

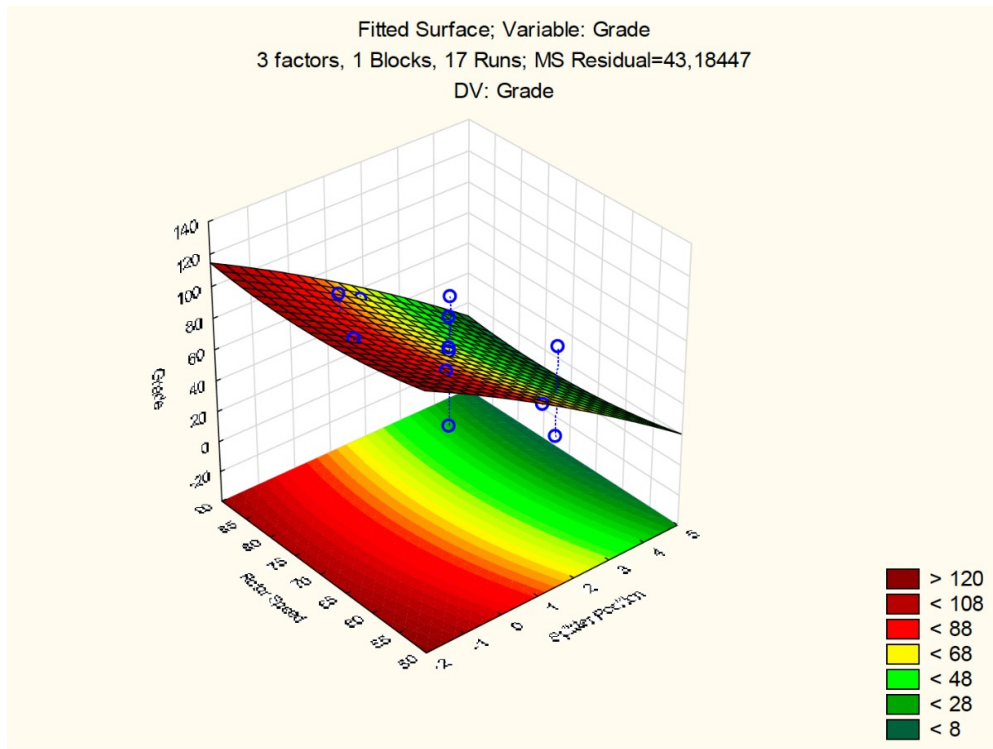


Figure 27: Fitted surface of grade against rotor speed and splitter position.

The behavior of grade with splitter position and belt speed is studied. While the rotor speed is maintained at a coded value of zero or a real value of 70Hz. The fitted surface in Fig 28 shows that the lower belt speed and a negative splitter position yields a higher grade. Negative splitter position means that splitter is far from the belt.

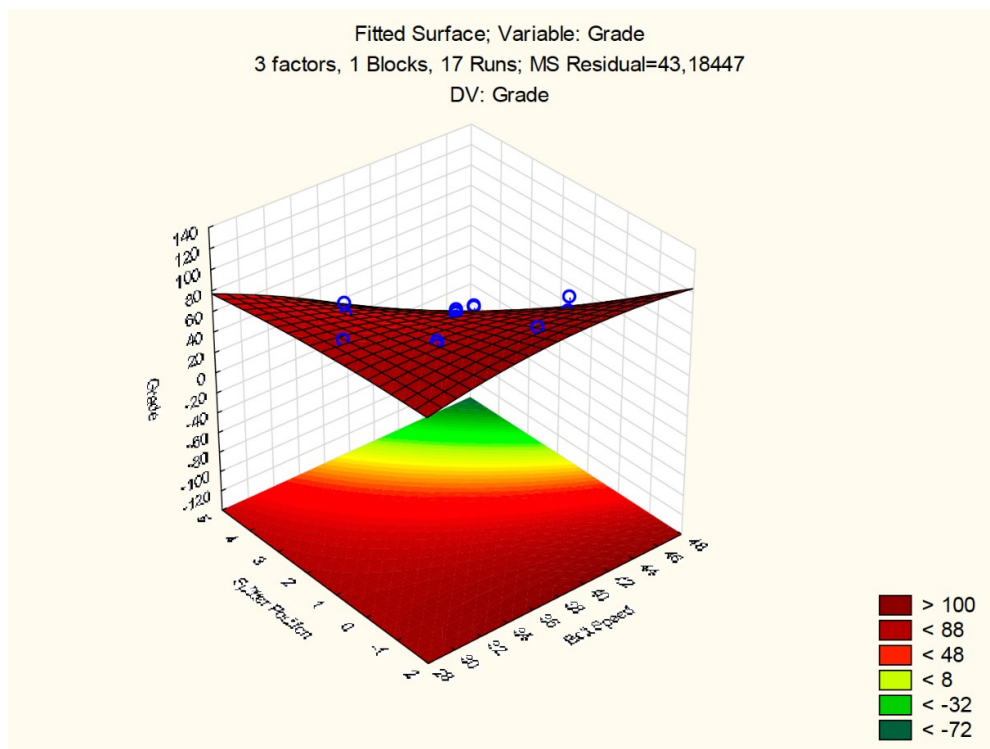


Figure 28: Fitted surface of grade against splitter position and belt speed.

The observed and predicted values of the grade are shown in the Fig 29. The graph shows that the values are correlated.

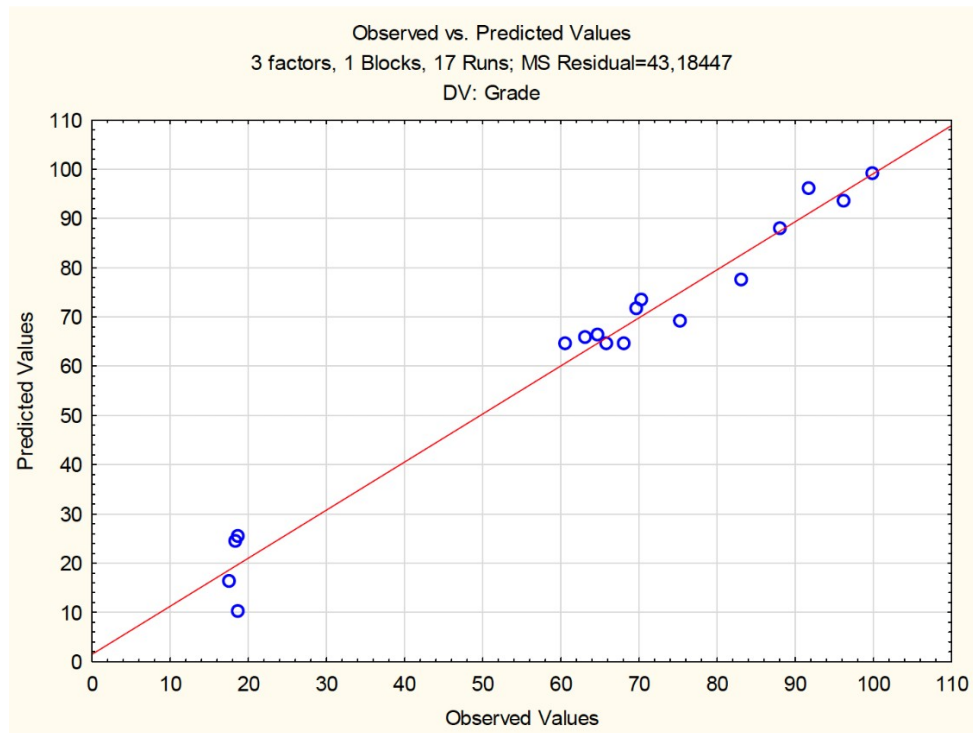


Figure 29: Observed and predicted values for grade.

Grade Model: The model equation for grade is given as follows

$$Y = 47.28 + 8.16x_1 - 0.18x_1^2 + 30.62x_2 - 0.35x_2^2 - 2.06x_3 + 0.02x_3^2 - 1.14x_1x_2 - 0.02x_1x_3 - 0.004x_2x_3$$

From the model equation it is evident that the independent variables x_1 and x_2 had more effect on the grade. Where x_1 is belt speed and x_2 is splitter position. Splitter position had a higher effect on the grade as compared to the belt speed. While x_3 (rotor speed) had a negligible effect on the grade.

4.5: Separation of individual fractions:

As the weight of one sample was 1000g and it was not enough to get an adequate amount of material after separation, so all six individual samples were merged to make a greater homogenized sample. 4 more tests were designed for the separation of metals, glass and wires. These tests were chosen based on high grade and recovery of the relevant material in the previous 17 test runs.

For example, for metals the highest grade and recovery were observed in the run 7. Run 7 yielded a metal grade of 75% with a recovery of about 63%. So, values of working

parameters from run 7 were chosen for run 18 to separate Al and Cu from the feed. To separate aluminum from copper all the tests with higher metal grade and recovery were analyzed. The reason for that was to see where we had higher separation of aluminum and copper in concentrate and tailings respectively. In some tests both the metals ended up in either concentrate or tailings. Run 3, run 7, run 8 and run 11 showed separation of the metals to some extent. The separation results are summarized in the table 16 which shows the percentage of aluminum and copper recovered in the concentrate and the tailings. The table shows that in run 3, 57% of Al is collected in concentrate while 59% of Cu is collected in the tailings. Run 3 showed better separation than the rest of the test runs, so this run was chosen to separate Al and Cu in run 19.

Table 16: Separation percentages of Al and Cu in concentrate and tailing

	Concentrate				Tailings				Feed	
	Al (g)	Al (%)	Cu (g)	Cu (%)	Al (g)	Al (%)	Cu (g)	Cu (%)	Al (g)	Cu (g)
Run 3	75.23	57	17.59	41	57.08	43	25.34	59	132.31	42.93
Run 7	79.91	60	30.52	72	52.99	40	11.64	28	132.9	42.16
Run 8	68.41	52	18.41	44	63.81	48	23.83	56	132.22	42.24
Run 11	18.23	14	1.53	4	114.51	86	41.19	96	132.74	42.72

Similarly to separate glass and stones, the 17 test results were analyzed. The better separation results are summarized in the table 17. The best separation was in run 14 where almost all the glass ended up in concentrate and about 38% stones ended up in the tailings. So, to separate glass from the rest, the working parameters of run 14 were chosen for run 20.

Table 17: Separation percentages of Glass and stones.

	Concentrate				Tailings				Feed	
	Stones (g)	Stones (%)	Glass (g)	Glass (%)	Stones (g)	Stones (%)	Glass (g)	Glass (%)	Stones	Glass
Run 4	249.1	70	249.9	99.6	109.3	30	1.08	0.4	358.4	251.0
Run 9	232.8	65	255.7	98	123.7	35	4.2	2	356.5	259.9
Run 12	231.9	65	254.9	98	122.7	35	5.4	2	354.6	260.3
Run 14	220	62	258.8	99.7	134.7	38	0.79	0.3	354.7	259.6

Also, the separation results for wires are shown in table 18. All the tests where recovery of wires was high were chosen. Run 15 shows that 75% of the wires were recovered in the concentrate while 85% of composite material was collected in the tailings. Thus, the working parameters of run 15 were chosen for the run 21.

Table 18: Separation percentages of Wires and composites.

	Concentrate				Tailings				Feed	
	Wires (g)	Wires (%)	Comp (g)	Comp (%)	Wires (g)	Wires (%)	Comp (g)	Comp (%)	Wires	Comp
Run 3	20.95	59	13.27	17.3	14.7	41	63.5	82.7	35.65	76.77
Run 5	17.4	51	26.74	35	16.62	49	50.34	65	34.02	77.08
Run 9	35.41	100	68.24	90	0	0	7.93	10	35.41	76.17
Run 15	26.54	75	11.89	15.5	8.84	25	64.92	84.5	35.38	76.81

The flowsheet for the whole separation process for metals and other materials is shown in Fig 30. The scheme shows the test scheme for individual materials to be separated. Run 18 was conducted to concentrate the metals (Al and Cu together in the concentrate). While in the run 19 (cleaning stage), Al was collected in the concentrate and copper in the tailings. The tailings of run 18 were subjected to subsequent cleaning stage (run 20) to recover glass in the concentrate while removing most of the stones in tailings. Another stage (run 21) was introduced to recover wires in the concentrate. In run 21 the composite material was collected in the tailings.

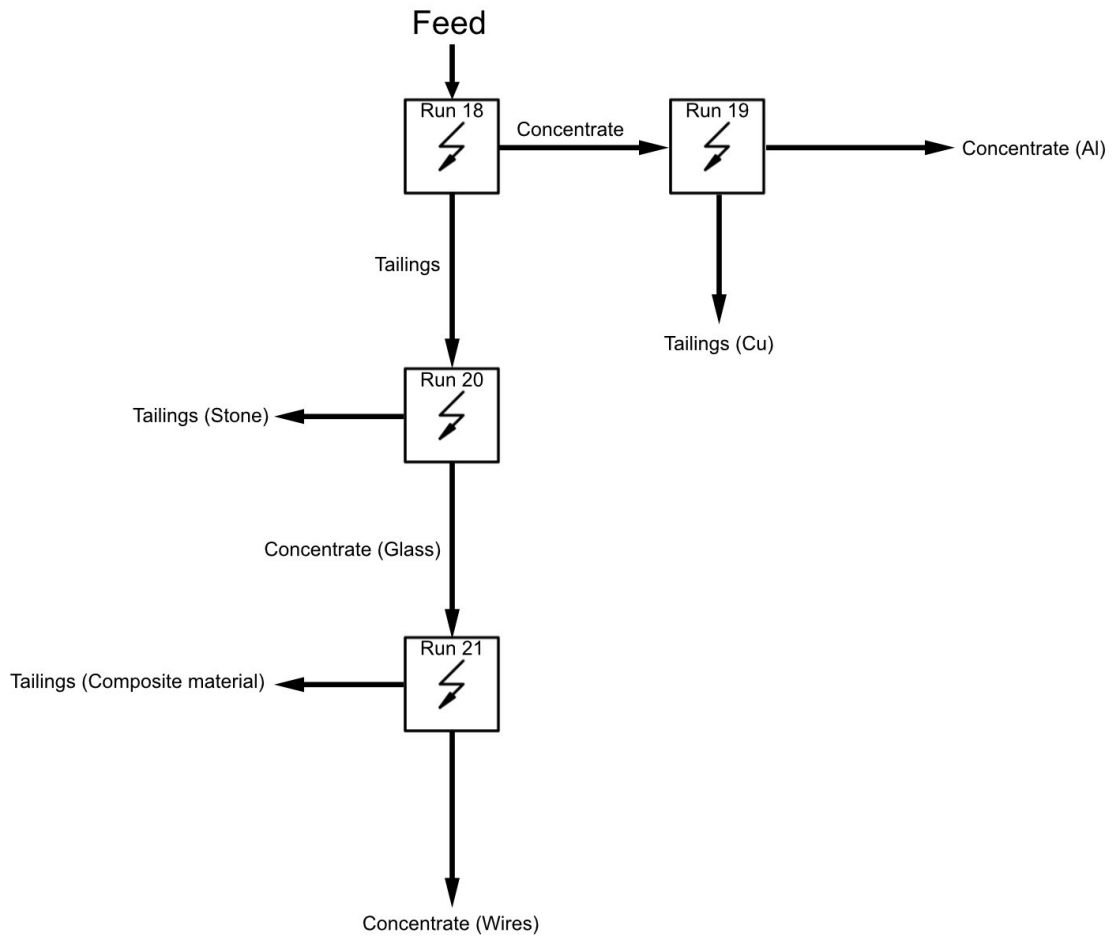


Figure 30: Flowsheet for metals and other material separation by ECS.

The results of individual material separation are tabulated in the following table 19. The recoveries of the material are shown in either the concentrate or the tailings depending on where the material was collected. Recovery in concentrate is shown on the left side of the column while recovery in tailings is shown on the right side of the recovery column. In run 18, both Al and Cu/Brass were collected in the concentrate. While in run 19, about 87.85% of Al was recovered in the concentrate and 20.04% Cu/Brass was recovered in the tailings.

In run 20, 99.29% glass was in concentrate while 35.2% stone was in tailings. Similarly, in run 21, about 19% wires were collected in the concentrate and about 94% composite material was collected in the tailings.

Table 19: Recoveries of individual materials in Concentrate or Tailings.

Run No	Material	Feed (g)	Concentrate (g)	Tailings (g)	Recovery in C or T %
18	Cu/Br	256.89	169.05	87.84	65.81
18	Aluminum	795.62	531.75	263.87	66.83
19	Cu/Br	169.05	135.16	33.87	20.04
19	Aluminum	531.75	467.13	64.55	87.85
20	Stone	2092.15	1355.97	736.18	35.19
20	Glass	1529.21	1518.40	10.81	99.29
21	Wires	100.36	19.00	81.36	18.93
21	Composite	278.94	17.56	261.38	93.70

The recoveries of the individual products like Al, Cu/Brass, glass and wires are shown in the following Fig 31. The figure shows the recoveries in concentrate and tailings.

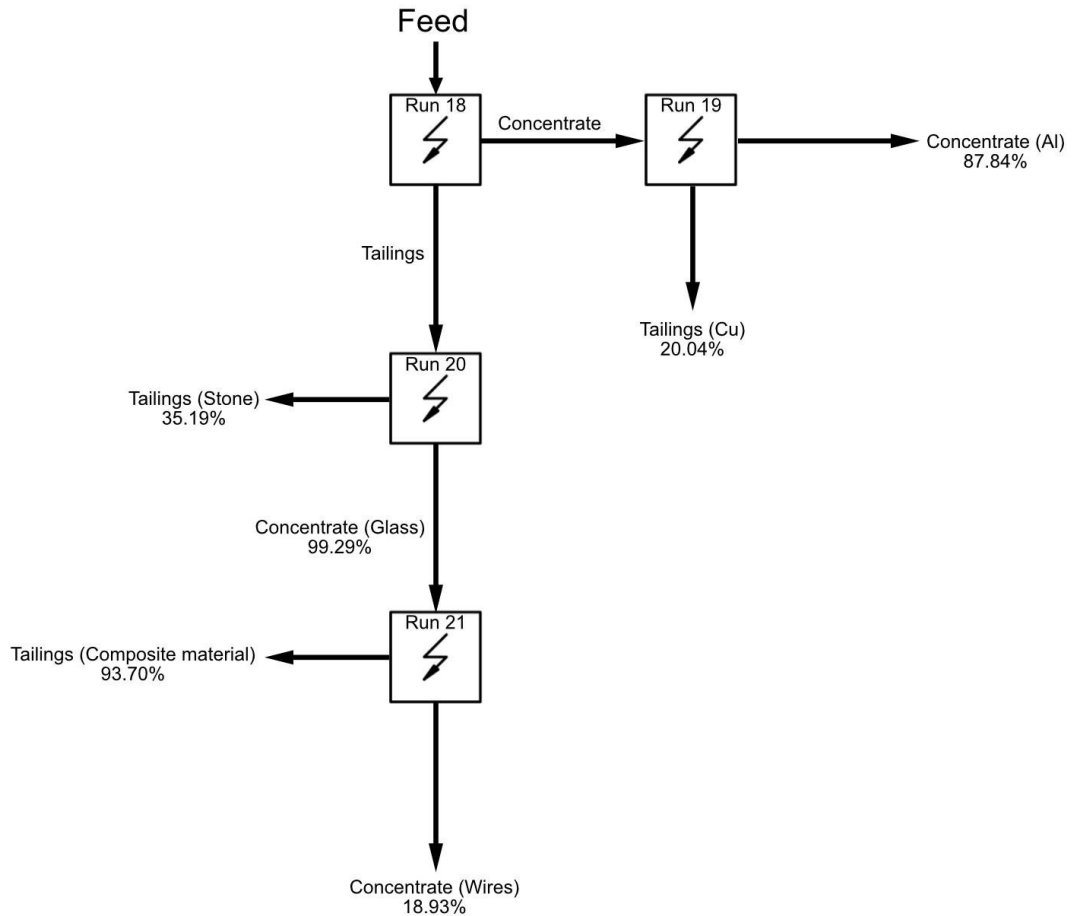


Figure 31: Recoveries of individual products in the relevant streams in ECS.

4.5.1: Material Balance:

The material balance for the run 18 to 21 was also calculated and is presented in the table 20. The material flowing into the run number 18 and the material flowing out from the other streams should be equal. Material going into the stream is feed and the composition of feed was known. This is shown in the material in column of the table. Material flows out in the concentrate and tailings of run 19, tailings of run 20 and both the concentrate and tailings of the run 21. All these values are added up in the material out column of the following table. It can be seen from the table that the material flowing into the system is equal to the material flowing out of the system.

Table 20: Material Flow and Balance for tests 18-21.

	Run 18	Run 19		Run 20		Run 21		
Feed	Material In %	Conc	Tails	Conc	Tails	Conc	Tails	Material Out %
Plastic	9.74	0.00	0.10	8.90	0.73	0.08	8.82	9.74

Cu/Br	4.29	2.26	0.57	1.17	0.30	0.28	0.89	4.29
Aluminu m	13.29	7.80	1.08	2.59	1.81	0.50	2.09	13.29
Stone	35.41	0.20	0.28	22.66	12.75	0.12	22.08	35.43
Glass	26.05	0.01	0.49	25.37	0.18	0.26	25.11	26.05
Wires	3.54	0.84	0.98	1.68	0.01	0.32	1.36	3.51
Composit e	7.68	1.21	1.26	4.66	0.56	0.29	4.37	7.68
Total	100.00							99.99

The sequence of material flow and balance are shown graphically in the Fig 32.

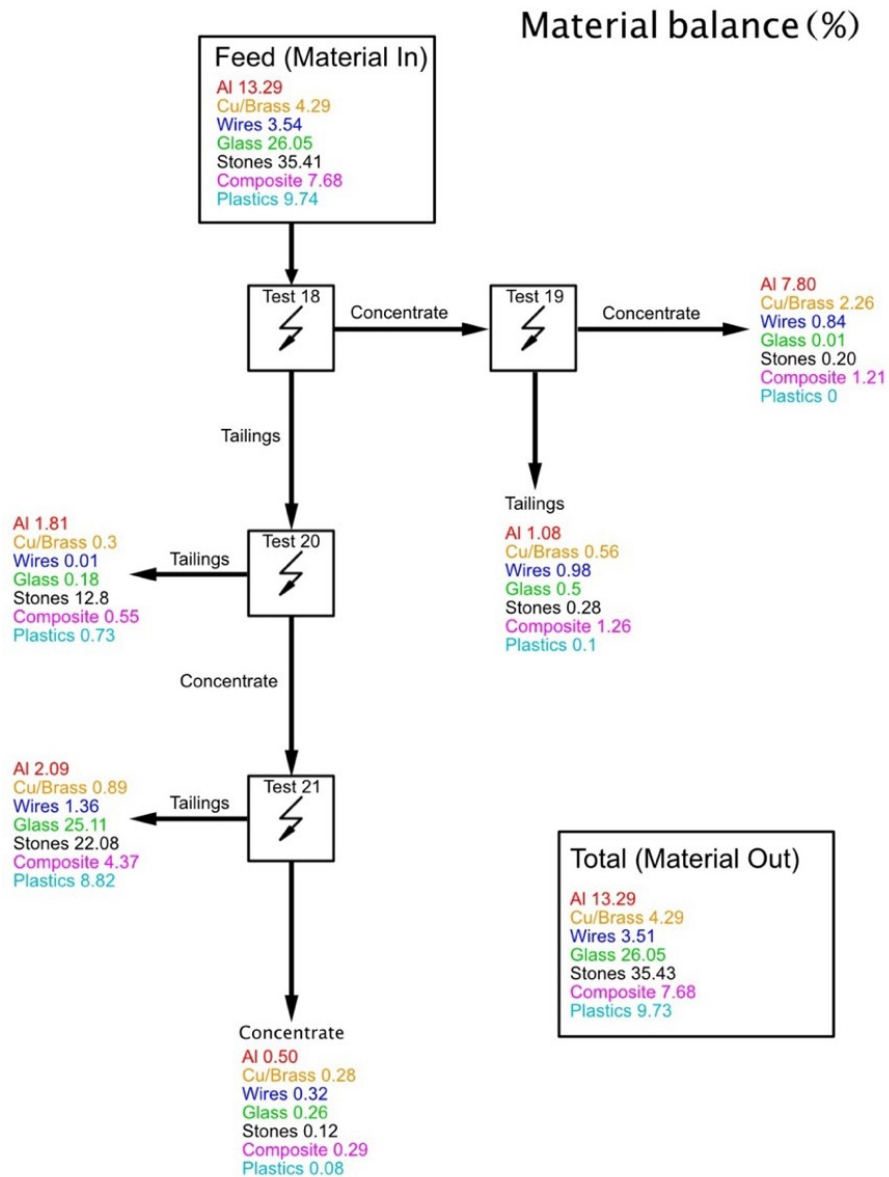


Figure 32: Material balance and flow for ECS.

4.6: Comparison of ECS and OS:

For optical separation the grade and recoveries of the individual products are shown in the table 21 below. 84% wires were collected in the concentrate at a grade of about 30%. 85% of glass at 93% grade was collected in the glass concentrate. Regarding Al, about 84% Al was in Al concentrate with a grade of about 25%. While for Cu/Brass, around 24% was recovered in the respective concentrate at a grade of about 22%.

Table 21: Grade and Recovery of individual products after optical separation.

Element	Feed		Concentrate		Tailings		Recovery %
	Weight (g)	Grade %	Weight (g)	Grade %	Weight (g)	Grade %	
Al	704.61	17.67	617.78	24.91	86.83	5.76	87.68
Cu/Brass	154.14	10.22	36.80	21.85	117.34	8.76	23.87
Glass	1534.97	28.54	1296.68	93.21	238.29	5.98	84.48
Wires	211.74	3.54	177.53	29.62	34.21	0.64	83.85

ECS: The calculated grade and recovery for each individual product after ECS is shown in the table 22 below. It is seen that 88% Al is recovered at a grade of 63%. Cu/Brass has a recovery of 20% in tailings with a grade of 18%. In case of wires, the recovery is about 19% at a grade of 17%. While for glass the recovery was 99% at a grade of 38%.

Table 22: Grade and Recovery of individual products after ECS

Element	Feed		Concentrate		Tailings		Recovery %
	Weight (g)	Grade %	Weight (g)	Grade %	Weight (g)	Grade %	
Al	531.75	52.03	467.13	63.39	64.55	22.67	87.85
Cu/Brass	169.05	16.54	135.16	18.34	33.87	11.90	20.04

Glass	1529.21	30.81	1518.40	38.11	10.81	1.10	99.29
Wires	100.36	2.52	19.00	17.05	81.36	2.10	18.93

The table 23 below shows a grade and recovery comparison of both the test procedures. ECS produced a higher grade (63%) concentrate of Al with a recovery of about 88% while Optical sorting produced a similar recovery but with far lesser grade. So, for Al, ECS performed better than the Optical separation process.

In case of Cu/Brass, both the processes had comparable results. ECS yielded 20% recovery of Cu/Brass with a 18% grade while Optical sorting produced a concentrate with 24% recovery and 22% grade. So, optical sorting takes a bit of edge with Cu/Brass.

Comparing wires, ECS produced a concentrate with 19% recovery and a 17% grade while optical sorting produced a concentrate of 84% recovery with a 30% grade. So, in case of wires, optical sorting outperformed the ECS.

For glass, ECS had a recovery of 99% with a 38% grade while optical sorting process had a recovery of 84% with a very high grade of 93%. Optical sorting process performed very good in terms of both recovery and grade for glass.

Table 23: Grade Recovery Comparison of ECS and OS

Element	Eddy Current Separation		Optical Sorting	
	Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
Al	63.39	87.85	24.91	87.68
Cu/Brass	18.43	20.03	21.85	23.87
Wires	17.05	18.93	29.62	83.84
Glass	38.11	99.29	93.21	84.48

In terms of grade Optical sorting process performed good for wires. It produced a concentrate of 30% for wires. And for glass, optical sorting produced a concentrate with a grade of 93%. However, for Cu/Brass, optical sorting did almost the same as ECS. While for Al, optical sorting did not produce a high-grade concentrate. For Al, ECS worked very well and produced a high-quality concentrate. This can be seen in fig 33 which shows the grade comparison of both the processes. Optical separation process had higher grades for glass and wires as compared to ECS. However. ECS produced a high-grade concentrate of Al in comparison to optical separation.

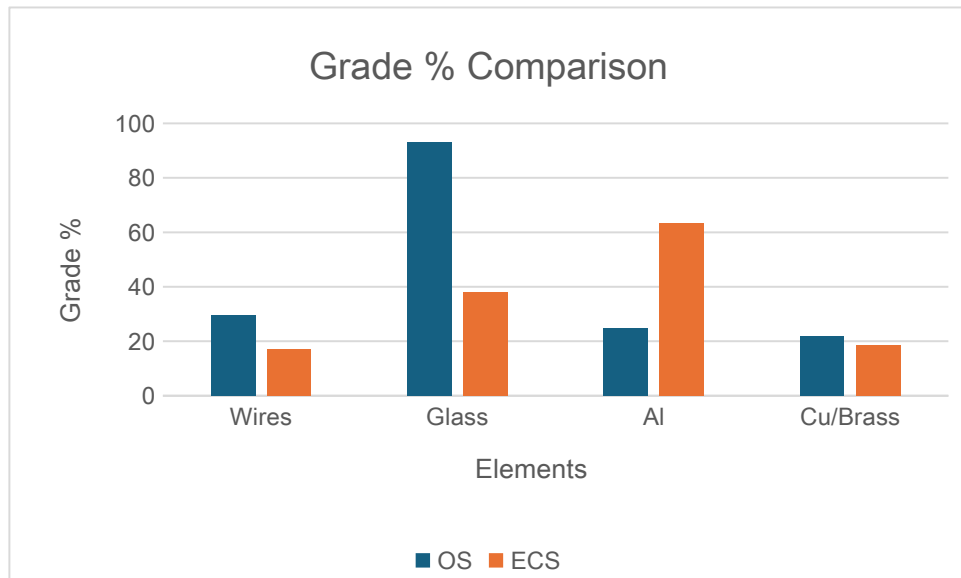


Figure 33: Grade wise comparison of Optical separator and ECS.

In terms of recovery, optical sorting process worked very well for wires. ECS produced a low-quality wires concentrate. For Cu/Brass, Optical sorting produced a bit higher recovery as compared to ECS. In case of glass, ECS had a higher recovery. And for Al, both the processes produced a similar recovery. It is shown in fig 34.

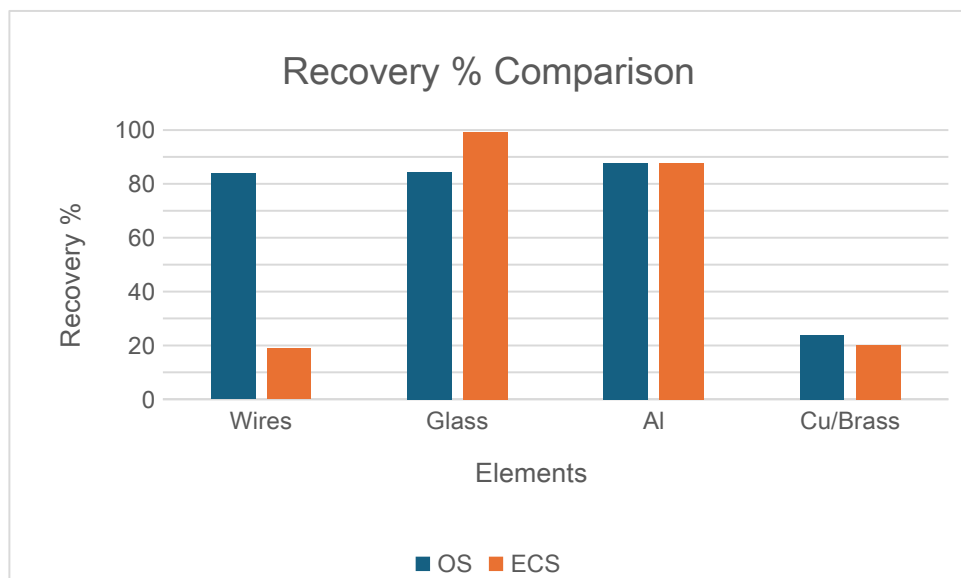


Figure 34: Recovery based comparison of Optical separator and ECS.

4.7: Outlook:

The results of the both the processes are different due to the differences in the nature of the separation criteria. This allows us to integrate these processes to our benefit. Combining the ECS and optical separator can help us improve recovery of metals and other products. Recovering wires and glass with optical sorting and then using ECS for Al would prove to

be more efficient. Introducing them at the right position in the material flow stream can largely improve the recovery. This way we can utilize the strengths of each process for maximum recovery of the individual materials.

Some other sorting processes can be researched as well to complement the overall recovery of the individual products. For example, density separation can be an option for sorting Cu and other fractions, but this has yet to be confirmed by some future research. Figure 35 below shows a proposed flowsheet for maximizing the recovery.

Proposed flowsheet

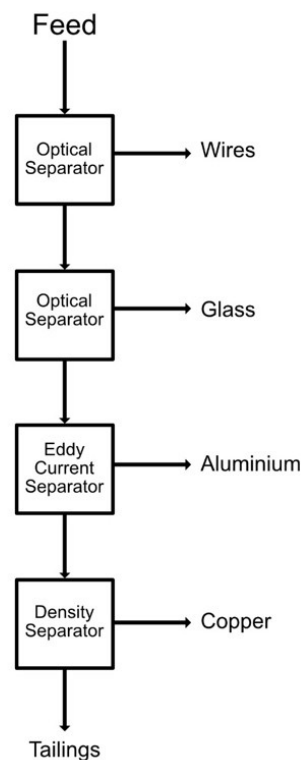


Figure 35: Proposed flowsheet for optimum recovery of individual materials.

The goal should be to produce cleaner products and to minimize the amount of valuable material (metals) ending up in the final tailings.

The separation/sorting behavior should be analyzed with different particle size as well to see if the results are different.

5: Conclusions and Recommendations:

DoE allowed to analyze the impact of the independent variables on the recovery and grade which were the dependent variables. It was seen that both the dependent variables were influenced highly by splitter position and belt speed respectively. While rotor speed had negligible effect on grade and recovery.

Sieve analysis showed that the feed material was quite coarse and the D80 was 4.8mm. However, increasing recovery lowered the grade and vice versa.

None of the processes produces a cleaner product. However, they produce a high-quality concentrate for some materials. Optical separator works very well for glass and wires while ECS works good for Al. ECS produced a high-grade concentrate of Al with a higher recovery as compared to OS. At the same time, OS worked very well for the materials to be separated based on either transparency or shape. In case of glass, OS produced a very high-grade concentrate with a high recovery. Also, OS produced a high recovery and a better grade for wires as compared to ECS.

It is recommended to use both the processes together in the stream so to maximize the recovery of each material. OS can be used for recovering glass and wires, while ECS can be used for Al. Capabilities of both the processes can be used to improve recovery.

6: Summary:

Every year about 83% of the WEEE goes un-recycled in the world. Besides having the environmental impacts due to seepage of metals and hazardous substances into earth, billions of dollars of lost as well. There is a lot of potential to recover raw materials from this waste stream and bring them to a circular economy model. This will also help reduce the pressure on the natural resources.

Of the collected waste, only about 40-45% is recycled and the rest still goes to landfills. With this thesis, an effort was made to compare which process performs better for the separation of the metals and other individual fractions, so that we can improve the resource recovery from this waste stream. By increasing the resource recovery, not only will we be able to add those materials into the loop again (circular economy), but it will also contribute to the economic development.

The material to be analyzed was sampled at the working facility of spectra media which was then tested with both optical separator and Eddy current separator. Before beginning with the test work, the material was manually sorted by look and pick method. This allowed to characterize the feed and thus to calculate grade and recovery for each individual fraction after every test. Same feed material was used to run the experiments with both the processes. Sieve analysis showed D80 to be 4.8mm thus the tests were conducted on a rather coarse material. The grade and recovery curve showed that as the recovery increases the grade decreases and vice versa. Due to the limited time, more research could not be done to analyze other sorting methods.

A DoE was designed for the initial test phase with ECS to find out the influence of the independent variables on the process and to get the best parameters for optimum separation of individual materials. It was found out that the grade and recovery are influenced the most by splitter position and belt speed respectively. While the rotor speed had negligible effect on both the dependent variables (grade and recovery). The other key findings of the thesis are that Optical separation produced good quality concentrates for wires and glass. Wires were separated based on the shape of the particles while glass was separated based on transparency and reflective properties. However, for Al optical sorting was not very useful as it sorted all the grayish material along with it. ECS on the other hand, produced a high-grade concentrate for Al as compared to optical sorting.

Optical sorting worked very well for the materials to be separated based on either shape of the particles or transparency. But when it comes to separation based on color, the process

gets inefficient due to the mixed and heterogeneous nature of the WEEE. All the materials with somewhat similar color are wrongly sorted into the concentrate instead of tailings. It is recommended to perform further studies by combining both ECS and optical separator to maximize the recovery of individual products. This way we can utilize the capabilities of these processes to our advantage. To separate Cu from other material, density separation process can prove to be very efficient.

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