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WEEE4Magnets: Optimizing the use of Waste Electrical and Electronic Equipment for the production of permanent magnets.

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And just like that, this work completes a cycle that started in October 2022. A lot of time has passed with moments of joy, pride, laughter but also moments of sadness, dissatisfaction and disappointment. Most important of all, however, are the new experiences and friends acquired during this time, and for that it would be worth repeating the same process. This work closes my post-graduate course with the title: WEEE4Magnets: Optimizing the use of Waste Electrical and Electronic Equipment for the production of permanent magnets. Prepared in the framework of HORIZON2020 project – Plooto – Product passport through twinning of circular value chains.

At this point I want to thank the lovely Assistant Professor Mr. Kaparis who put up with me all this time and gave me the opportunity to work with him. I also owe a huge thank you to Professor Andreas Georgiou who approved the start of this postgraduate thesis. I would like to thank Dr. Giorgos Zois and Mr. Kyriakos Bitsis who with their experience helped me in technical matters for the methodology followed to complete the experimental part of the project.

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Abstract

The recovery of waste electrical and electronic equipment (WEEE) has become a major issue for the solid waste management. Investigating new ways of WEEE disposal has become mandatory in most countries of the world. Designing a value chain to recover useful secondary raw materials and specifically magnetic materials for the production of permanent magnets is a promising direction to this end.

Initially, an overview of the literature was carried out regarding the project and the three pilots it includes. Then we delved into the specific pilot and the 3 companies that make it up. Historical data on the classification of WEEE and their magnetic content specifically for NdFeb and Sr-Ferrite magnet materials were then reviewed. This was followed by a general classification of the WEEE containing the largest amounts of NdFeb magnets, and how these flows have evolved from the beginning of 1990 until today.

Designing an optimal network for WEEE plays a crucial role in determining the overall energy cost of the recovery system. In this thesis, considering the uncertainty in grid operation, a preliminary linear programming model was developed for WEEE recovery to address the problem, which primarily stemmed from recovery uncertainty related to magnetic content percentage proportions and energy costs. These factors comprise synthetic data and notably deviate from constraints, enabling decision-makers to adjust the robustness level of the operating system.

The computations were performed using Excel and the results indicated that, given the input parameters, the linear programming model successfully calculated the total energy cost required for WEEE reuse to produce permanent magnets. At this early stage, the project is constrained by a significant shortfall in essential data: namely, baseline figures required for benchmarking purposes and operational data from the value network's factories. It is our expectation that, in the future stages of our research, these data gaps will be filled. This development is anticipated to provide a robust foundation for refining the proposed model and extracting further analytical insights.

Keywords: Permanent magnets, optimization, WEEE, linear programming, circular economy, recycling

Table of Contents

1 Introduction and Literature Review 8

2 Similar EU-Projects – Description of Plooto Project EU 22

  2.1 PLOOTO’s contribution 23

    2.1.1 Recycling of WEEE by FERIMET 27

    2.1.2 Re-Processing by IMDEA 30

    2.1.3 Magnets production by IMA 32

    2.1.4 Network Design 33

3 Total Network - Supply Chain 35

4 Methodology 41

  4.1 The Case Study – Methodology & LP Model 41

  4.2 Results and Discussion 47

5 Conclusions – Limitations – Future Research 63

6 Bibliography 66

TABLE OF FIGURES

FIGURE 1: DIFFERENT MATERIAL COMPOSITIONS IN WEEE 10
FIGURE 2: UPDATE OF WEEE COLLECTION, RATES, TARGETS, FLOWS AND HOARDING – 2021 [24] 15
FIGURE 3: NEODYMIUM WASTE GENERATED IN EU-28 COUNTRIES, GROUPED BY APPLICATION TYPE [25]. 16
FIGURE 4: GEOGRAPHIC DISTRIBUTION OF NEODYMIUM IN WASTE PER EUROPEAN COUNTRY IN 2019. 17
FIGURE 5: OVERVIEW OF THE MATERIAL RECYCLING AND RECOVERY PROCESS 28
FIGURE 6: INDICATIVE PFD OF DIFFERENT RECYCLING OPTIONS FOR PM IN WEEE 29
FIGURE 7 MINIMUM TARGETS FOR THE SEPARATE COLLECTION OF WEEE IN SPAIN IN 2023, FOR EACH CATEGORY 30
FIGURE 8: IMDEA PROCESS FLOW DIAGRAM 31
FIGURE 9: IMAS' PRODUCTION PROCESSES 33
FIGURE 10: OVERALL PROCESS FLOW DIAGRAM 36
FIGURE 11: DIFFERENT TYPES OF WEEE 37
FIGURE 12: DEMAGNETIZATION EQUIPMENT 38
FIGURE 13: HOMOGENIZER 39
FIGURE 14: PROPOSED TOTAL NETWORK FOR OPTIMIZATION 44
FIGURE 15: FULL SPECIFICATION OF THE OPTIMIZATION MODEL AND THE OBJECTIVE FUNCTION 46
FIGURE 16: MODEL SOLUTION 47
FIGURE 17: OBJECTIVE FUNCTION SOLUTION 47
FIGURE 18: SENSITIVITY ANALYSIS 48
FIGURE 19: SENSITIVITY ANALYSIS 55
FIGURE 20: SOLUTION RESULTS, IF WE CHANGE THE DEMAND FOR SR-FERRITE 56
FIGURE 21: CONSTRAINTS, AFTER THE CHANGE OF THE DEMAND FOR SR-FERRITE 57

LIST OF TABLES

TABLE 1 OVERVIEW OF THE 6 MAIN CATEGORIES FOR E-WASTE 9
TABLE 2: SUBSTANCES & SOURCES APPLICABLE 11
TABLE 3: WEIGHT OF METALS IN WEEE [26] 18
TABLE 4: ANALYSIS OF THE BUSINESS CASES, INSIDE PLOOTO PROJECT 26
TABLE 5: RECYCLING OPTIONS FOR MAGNETS [18] 28
TABLE 6: ENERGY COSTS FOR XIJ (MONEY UNITS/KG) 41
TABLE 7: PROPORTIONS OF EACH MAGNET COMPONENTS INSIDE EACH WEEE TYPE (A_{IJ} %) 41
TABLE 8: DATA REGARDING THE CAPACITY FOR EACH TYPE OF WEEE THAT FERIMET CAN ACCEPT AND PROCESS INSIDE THEIR FACILITY (CAP_J IN KG) 42
TABLE 9: NOTATION SUMMARY 45

1 Introduction and Literature Review

Recently, there has been a global shift towards repurposing waste into high-value products. This shift, driven by the critical need to mitigate environmental pollution and address the uncontrolled disposal of Waste Electrical and Electronic Equipment (WEEE) in landfills, has spurred enhanced research and development efforts. The above statement is included in Directive 2012/19/EU of 4 July 2012, the subject of which are the proposed measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of WEEE and by reducing overall impacts of resource use and improving the efficiency of such use, thereby contributing to sustainable development [29].

However, it is very important to fully understand certain definitions. Waste means any substance or object which the holder discards or intends or is required to discard, while waste electrical and electronic equipment or 'WEEE' means electrical or electronic equipment which is waste within the meaning of Article 3(1) of Directive 2008/98/EC [29], including all components, sub-assemblies and consumables which are part of the product at the time of discarding. WEEE are a category of waste, consisting of equipment at the end-of-life (EoL), powered by electricity or through electromagnetic fields and designed for use in a voltage not exceeding 1000 volts AC and 1500 volts DC. Each product is stamped from 13 August 2005 to identify its manufacturer and a pictogram showing that this product is the subject of a separate collection (standard EN 50419).

The tremendous speed of technological development has led to an exponential growth in the production of WEEE. To contribute to sustainable consumption and production and address the environmental issues related to the rapid growth of discarded electronics, the European Commission introduced the WEEE directive [16]. The directive includes equipment that is used for the generation, transfer or measurement of the currents and field and is limited to equipment designed for use with a voltage rating of up to 1,500 volts or 1,000 volts for alternating and direct currents respectively.

However, not all EEE yield WEEE at their EoL after being discarded. Products that meet specific conditions are excluded from WEEE categories and thus also exempted from the WEEE directive. Examples of exemptions are equipment designed to be sent into space, large scale stationary industrial tools, large, fixed scale installations, equipment designed for research and development and so on. In addition, WEEE do not include batteries, accumulators, or electrical components of vehicles.

Since EEE and WEEE are comprised of a wide variety of products, they have been categorized into 54 different product-centric categories, which are grouped into 6 general categories: temperature exchange equipment, screens and monitors, lamps, large equipment, small equipment and small IT and telecommunications equipment. The definitions and examples for the EEE categories that are covered by the WEEE directive are shown in *Table 1*.

Table 1 Overview of the 6 main categories for e-waste

Category	**Definition**	**WEEE examples**
Temperature exchange equipment	EEE with internal circuits where substances other than water are used for cooling, heating or dehumidifying.	Cooling and freezing equipment such as refrigerators, freezers, air conditioners and heat pumps.
Screens and Monitors	EEE intended to provide images and information on an electronic display regardless of its dimensions.	Televisions, monitors, laptops, notebooks, and tablets.
Lamps	Replaceable electronic devices that produce light from electricity and may have other functions.	Fluorescent lamps, high discharge lamps and LED lamps.
Large Equipment	EEE that does not belong to categories 1, 2 or 3, with any external dimensions over 50cm.	Washing machines, clothing dryers, dishwashers, electric stoves.
Small Equipment	EEE that does not belong to categories 1, 2, 3, 4 or 6, with no external dimensions exceeding 50cm.	Vacuum cleaners, microwaves, calculators, video cameras.
Small IT and telecommunication equipment	Information equipment that can be used to the collection, transmission, processing, storage and showing of information. Telecommunication equipment is designed to transmit signals electronically over a certain distance.	Mobile phones, routers, printers, Global Positioning System (GPS) Devices.

The WEEE EU-Directive states that electronics not tailored the specific application and products containing batteries should fall under WEEE. However, electric vehicles and batteries have their own directives, such that their electric components do not fall under WEEE, which may cause confusion in the scope of WEEE. Another example to elucidate confusion is that while all lighting equipment falls under the directive, filament bulbs are excluded.

WEEE is a non-homogenous complex mixture of materials that can contain up to 100 different substances, where the composition varies depending on the functionality and design. The material constituents of WEEE can be grouped into 5 main categories: ferrous metals, non-ferrous metals, glass, plastics and other. *Figure 1* shows the different material compositions in WEEE, where it is clear that metals make up a large majority (approximately 60%), followed by plastics and other constituents.

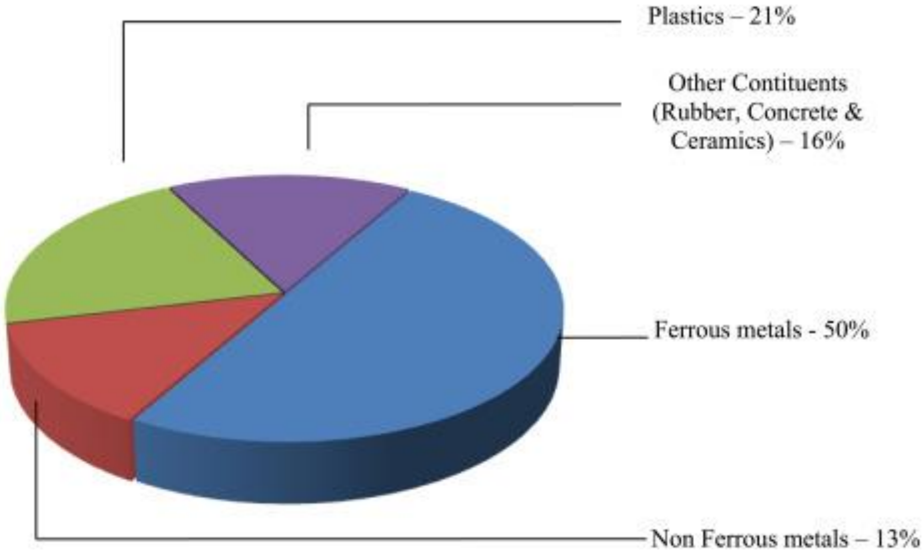


Figure 1: Different material compositions in WEEE

WEEE can contain a mixture of hazardous and non-hazardous materials that require special handling and recycling processes to avoid negative environmental and health related impacts. Examples of hazardous materials include the presence of heavy metals such as lead (Pb), nickel (Ni), cadmium (Cd), mercury (Hg), arsenic (As), selenium (Se), hexavalent chromium (Cr(VI)), and brominated flame retardants (BFRs), polybrominated diphenyl ethers (PBDEs) beyond the threshold quantities. An overview of sources of hazardous materials can be found in

Table 2, where some elements by themselves, such as Zn and Pb, are not hazardous but their applications are.

Table 2: Substances & Sources applicable

Substance		**Sources**
Lead	Pb	CRTs, television sets, monitors, batteries, printed circuit boards*, light bulbs*, lamps*
Cadmium	Cd	Ni-Cd batteries, contacts and switches*, semiconductor chips
Mercury	Hg	Lighting devices for flat screen displays, CRTs, PCBs, thermostats*
Chromium or hexavalent chromium compounds	Cr	Metal housing (anti-corrosion coatings)*, data tapes, floppy disks
Nickel	Ni	Ni-Cd batteries, electron gun in CRTs
POPs including BFRs	-	Circuit boards (fire retardants for electronic equipment)*, plastic casings for computers*, cables*, dielectric fluids in capacitors and transformers*, lubricants and coolants in generators*, fluorescent lighting*, electric motors*, connectors*
Lithium	Li	Li batteries
Barium	Ba	CRTs, fluorescent lamps*
Zinc	Zn	CRTs, metal coatings*, batteries
PVC		Insulation on wires and cables*
Beryllium	Be	Power supply boxes*, computers, ceramic components of electronics
Arsenic Americum	As Am	Gallium arsenide in LEDs* Smoke detectors*
Antimony	Sb	Flame retardants in plastics*
Chlorofluoro carbon	FCs	Cooling units*, insulation foams*
Polychlorinated biphenyls	PCBs	Condensers, transformers*
PBDEs, PBBs	-	Flame retardants in plastics*

It was anticipated by Boulding (1966) in a seminal paper that human beings would need to find their place in a circular ecological system where the resources are reduced, reused, or recycled [6]. Today, numerous businesses and industries depend on resource extraction and depletion, being confined on the linear economic model of “take-make-waste” actions [7] which assumes that resources are abundant, available, and cheap to dispose of. However, the constantly increasing need of scarce resources, raises the necessity of efficient resource usage, responsible waste management and prevention, as well as the reuse and recycling of materials to bring net savings to businesses (and consumers) while also reducing their environmental impact [8]. Manufacturing companies could benefit from the Circular Economy (CE) model, where products and resources can be reused, repurposed and recycled, aiming to maximize (i) the productivity of resources, (ii) waste reduction, and (iii) the quantity of byproducts that become raw materials (RMs) entering in other processes. Transitioning from the traditional linear production model to a circular one requires a focus on these aspects, which is precisely where the Plooto project focuses its efforts.

CE can be defined as “a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops” [12]. The main vision of the CE emphasizes the minimization of waste generation by enabling the circular use of materials and other resources in order to reduce the environmental footprint from resource extraction and break current destructive patterns of consumption and production. Currently, fully circular product systems do not exist at scale, with the exception of small-scale pilots for regional industrial symbiosis or partial products internal to a single firm [13]. Circular economy (CE) often necessitates a socio-technical transition, involving interactions between individuals and groups facilitated by technology and requiring significant behavioral shifts from consumers, businesses, and governments. This transition considers material flows, reverse supply chains, and material recovery strategies. The emphasis on material flows over energy in CE is justified due to the practical limitations on the supply of many materials, unlike non-fossil energy sources. The CE is based on fundamental underlying concepts, such as introducing cascading loops in the flows of materials that stem from the 1970s era when major schools of thought were established that sought to provide a systemic vision for transitioning to a sustainable economy. Cradle to Cradle, Biomimicry, Industrial Ecology, Natural Capitalism, and the Blue Economy represent major schools of thought, each assuming a different approach to achieving the transition. Indicatively, while Cradle to Cradle focuses on changing design practices for endless product lifecycles, Biomimicry seeks inspiration from nature's effective processes and systems, while the Blue

Economy emphasizes open-source collaboration and innovation. CE primarily aims to "close the loops" by redesigning products for longer lifecycles, along with recycling, reusing, and remanufacturing products and their components, while minimizing waste generation in production systems. Small material loops within supply chains are considered environmentally beneficial as they entail less material processing.

However, redesigning the reverse supply chain for accelerated recycling and enhanced material recovery demands digital technologies capable of collecting, sorting, and analyzing information on product and component locations and conditions. Additionally, making informed end-of-life decisions regarding component and material reuse requires real-time data on their status, maintenance, damage, and compositions. Current literature predominantly focuses on leveraging digital technologies to facilitate decisions regarding product repurposing, remanufacturing, reuse, and repair by facilitating information sharing among various stakeholders.

Furthermore, as supply chains have become more global and intricate, adopting CE practices requires transcending regulatory boundaries, as input from upstream supply chain partners is essential, and outputs may be distributed worldwide [14]. One additional challenge relates to moving from transparency and availability of data toward transforming that information into sustainability outputs. Transparency in itself does not lead to CE practices, but using the knowledge resulting from such transparency may lead to different trajectories and tactics to achieve them.

Digital product passports (DPPs) are envisioned as digital information tools holding product information pertaining to their entire lifecycle, from the extraction of raw materials and the manufacturing phases to shipping, distribution, and use until their end of life. Currently, several information tools exist that are used to certify certain properties and qualities of products, services, or processes. Recent advancements in digital technologies provide tools and methods for collecting and processing data from physical systems production processes, and product usage. This data can be collected and processed continually, in near-real time, and at scale, resulting in data sets with enormous potential for identifying inefficiencies. Consequently, novel data-driven design methods and tools for circular systems and processes that enable continual and fine-grained evaluation of their circular efficiency throughout the lifecycle management of a product or service can be developed [14].

The focus is on devising innovative methods to reclaim valuable materials (e.g. Rare-Earth Elements or ‘REEs’), for use as secondary raw materials in manufacturing of high value products. Rare-Earth Elements are gaining significance in the shift towards a green economy due to their essential role in permanent magnets, lamp phosphors, catalysts, and rechargeable batteries, among other applications. Neodymium (Nd), for instance, is utilized in over 85% of permanent magnets within the industry. In its seminal report, “Critical Raw Materials for the European Union (2020)” [1], the European Commission considers REEs as the most critical raw materials group, with the highest supply risk. The five most critical REEs are neodymium (Nd), europium (Eu), terbium (Tb), dysprosium (Dy), and yttrium (Y) [2]. Projections suggest a 700% surge in demand for Nd over the next 25 years, driven particularly by the growing adoption of hybrid and electric vehicles (HEV) and wind turbines [3].

There is a rapidly increasing demand for permanent magnets (PMs) in nowadays technological applications with a 7% annual increase mainly boosted by electric vehicles and green energy technologies. Access to enough rare earths (REs) is a real problem, based on a near-monopoly by China which results in extremely difficult political conflicts between countries and continued volatility in the prices of Res.

The constantly increasing demand of scarce resources and critical raw materials (CRMs), requires efficient usage of resources - reuse and recycling of materials- and responsible waste management and prevention. The circular economy’s model establishes a virtuous cycle where products and resources can be reused, repurposed and recycled to maximize productivity of resources, to reduce waste and by products that can become raw materials (RMs) entering in other industrial processes, thus reducing the depletion of natural resources and the overall environmental effects on climate change.

REEs production is centralized in China (accounting for the global production of over 90%), and exportation quotas have been imposed by the Chinese government, arousing concerns on the REEs supply risk at the European level. Moreover, as mining enterprises actively pursue fresh REEs deposits and old mines are being reopened, the construction of new mines frequently entails significant initial investment and timelines of more than 10–15 years before they can start operating [4]. Thus, the recycling of REEs could be far more economical and more readily achievable than the exploitation of new mineral deposits.

Despite vast efforts on REEs recycling, up to 2018, less than 1% of the REEs were recycled, mainly due to inefficient collection methods, technological challenges, and a lack of industry support for the recycling process. Consequently, a drastic improvement in the recycling of REEs is an absolute necessity that can only be achieved by developing efficient, fully integrated recycling routes, which can make use of the rich literature on REE recycling from WEEE [5]. The most promising candidate for the so-called 'urban mining' is the end-of-life products containing NdFeb magnets, while some actions have already been initiated in the recent past in this direction.

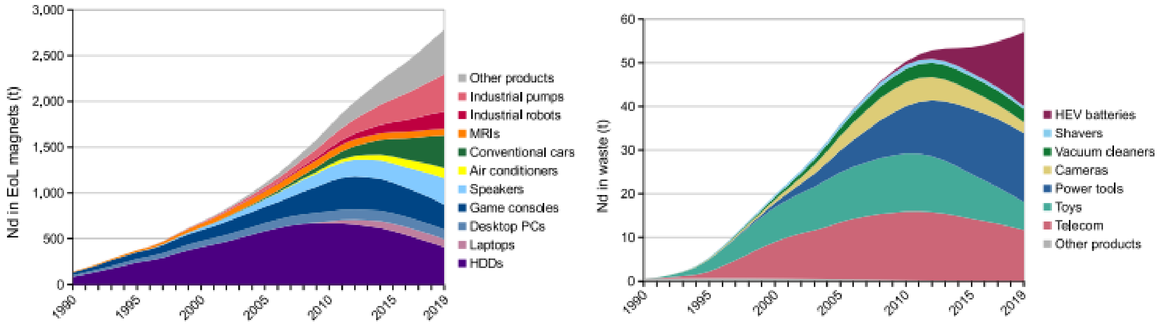
Materials and products which can be used as raw materials by simple re-use or via recycling and recovery are known as secondary raw materials (SRMs). SRMs can be classified in scraps and byproducts of industrial and mining processes, such as WEEE, which is the fastest growing waste stream in the EU (it was 10.5 kg per inhabitant in 2020) with a recycling rate less than 45.9% [9]. Interestingly, SRMs contain unharvested RMs (e.g., rare earths, Co, Nb) – so called critical RMs – whose availability is fundamental for the EU economy and are associated with high risk in terms of supply, as well base metals (e.g. Zn, Pb, Cu) at grades that are becoming competitive with the decreasing grades of primary ores [10].

Figure 2: Update of WEEE collection, Rates, Targets, Flows and Hoarding – 2021 [24]

An important factor to consider is the historical data on WEEE collection. As it seems from the above figure, the study reveals that the amount of EEE placed-on-market (POM) in the 27 Member States of the EU, Norway, United Kingdom, Switzerland, and Iceland increased from 9.8 million metric tonnes, (hereafter referred to as Mt), in 2010 to 13.3 Mt in 2019 (25.2 kg/inhabitant). The WEEE generated also shows an increase of 2.1 Mt, from 8.3 Mt in 2010 to 10.4 Mt (19.6 kg/inhabitant) in 2021. The documented formal collection of WEEE shows an increase of 1.8 Mt, from 3.8 Mt in 2010 to 5.6 Mt (10.5 kg/inhabitant) in 2021. The "WEEE

Generated method” is calculated by mass of WEEE collected divided by the mass of WEEE Generated in the same year. The collection rate increased from 40% in 2014 to 54% in 2021 using this method. These increments are primarily propelled by the substantial increase in WEEE collection compared to WEEE generation.

However, it is of major importance to look at the historical data regarding important raw materials that will be investigated in the context of this thesis, which are NdFeB & Sr-Ferrite.



(a) Neodymium contained in EoL magnets.

(b) Neodymium contained in EoL batteries and catalysts.

Figure 3: Neodymium waste generated in EU-28 countries, grouped by application type [25].

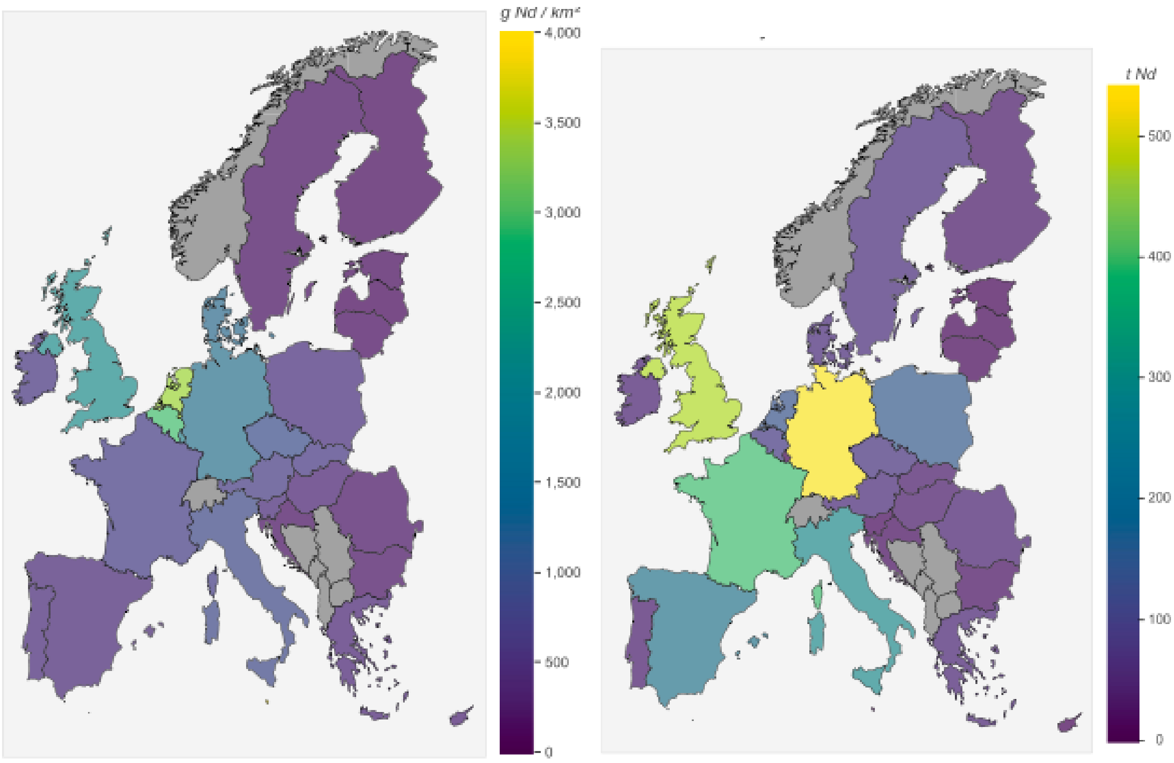
In contrast to the demand flow, the dominant source of Nd in waste is consumer electronics (*Figure 3*(a)). In 2019, 15% of the Nd waste flow originated from HDDs. Yet this amount has been declining from its peak in 2011, a trend also found for laptops, desktops and game consoles. Another important waste flow concerns speakers, which includes various audio devices such as professional loudspeaker systems, home audio, and smart speakers. Contrary to other consumer electronics, the demand for Nd in speakers has increased in recent years, with waste following with delay.

The last few years show an increase in Nd flows associated with EoL industrial robots and pumps. These waste flows represented 7% and 15% of all Nd waste in 2019. Due to the longer lifespan of these products as well as the increasing demand, these waste types are expected to continue to grow in the future. Over the whole range, a shift to product groups with longer lifespans is observed. Automotive and industrial applications are in use longer than consumer electronics, therefore the stock increases even with constant influx.

In contrast to End-of-Life (EoL) NdFeB magnets, other components containing neodymium (Nd) contribute relatively little to the overall Nd waste streams in Europe. According to *Figure 3*(b), in 2019, there was a waste flow of 57 kilotons of Nd, which represented only 2% of the total waste flow for that year. Within applications such as batteries and catalysts, there has been a growing amount of Nd sourced from hybrid electric vehicle

(HEV) batteries. Specifically, this pertains to Nickel Metal Hydride (NiMH) batteries commonly found in older generations of HEVs. However, as the market for HEVs and Battery Electric Vehicles (BEVs) shifts towards lithium-based batteries, this increase in Nd from NiMH batteries is expected to be temporary.

While the emergence of wind turbines and EVs is apparent in *Figure 3*(a), these categories are virtually absent in the overview of waste flows. Based on the long lifespan of wind turbines and EVs, significant waste flows are expected several years in the future. Such a delay due to the lifespan was also observed for Nd from conventional cars [25].



(a) Waste flow density.

(b) Total waste flow.

Figure 4: Geographic distribution of neodymium in waste per European country in 2019.

A comparison of annual Nd waste flows of European countries revealed large differences, as illustrated by *Figure 4*(a). The waste density varies with almost two orders of magnitude, amounting to 75 g/km^2 for Latvia and 6.5 kg/km^2 for Malta. Besides Malta, high waste densities are found in other densely populated countries, Belgium and the Netherlands. The variation is also high for the absolute volume of Nd waste, coinciding with differences in population size (*Figure 4*(b)). Unsurprisingly, the total Nd waste flow was largest in countries with a large population, such as Germany, France and the UK.

In contrast to the above, and in the context of the present thesis, Sr-ferrite should also be mentioned, which is an economically viable alternative to NdFeB. This substance can also be found in WEEE however in different quantities and concentrations depending on the waste. Ferrites are the most widely used permanent magnets throughout the world, accounting for about 90 wt % of all permanent magnets on a weight basis. The permanent magnet market size was valued above USD 15 billion in 2015. Ferrites are used in a multitude of technological applications that cover low-field and low-power applications, high-frequency systems, and biotechnology. On the basis of the high demand for this type of magnet, recycling of the WEEE, is beneficial from an environmental point of view but also economically interesting to reduce costs at the permanent magnet company while additionally guaranteeing sustainability by closing the loop in the production line [20].

As an indication, following a study carried out and published in 2021 in the Journal of Ecological Engineering, the following table shows the concentrations of Sr-Ferrite in Various WEEE [26].

Table 3: Weight of metals in WEEE [26]

Metal	Weight, t/y					
	Mobile phones	Computer mice	Keyboards	Web-cameras	Monitors	Total
Mn	6.293				0.386	6.679
Fe	406.103	0.036	32.615	1.84	305.342	745.936
Ni	90.081		0.578	0.096	1.811	92.566
Co	1.987		0.064			2.051
Cr	100.842				0.009	100.851
Hg			0.19			0.19
Pb			2.917	0.382	1.185	4.484
As					11.691	11.691
Sn	9.943	4.745	6.29		59.138	80.116
Zn	47.931	3.702	55.204	0.82	33.443	141.100
Cu	219.757	7.226	1.006	3.713	102.142	333.844
Zr	5.031		2.34		4.786	12.157
Mo	0.999			0.008	0.156	1.163

Ag	0.016		4.711		2.938	7.665
V	3.111			0.066		3.177
Sr	**233.013**	**0.01**	**0.13**	**0.324**	**226.053**	**459.530**
Rb		0.044	0.0002	0.372	0.462	0.878
Sb		0.272		3.906	2.251	6.429
Y			0.088		0.0003	0.088
Rh			1.858			1.858
Bi			0.0004			0.0004
Ga					0.0007	0.0007
Ba					0.436	0.436
Total	**1125.107**	**16.035**	**107.9916**	**11.527**	**752.23**	**2012.891**

According to this study, the metals with the highest weight in Waste Electrical and Electronic Equipment analyzed include iron, strontium, and copper. Particularly noteworthy is the relatively significant weight of strontium, primarily found in the glass of screens. It's evident that a considerable proportion of strontium is present in mobile phones and monitors.

The significance of ferrites is increasing due to the growing demand for permanent magnets in various technological applications, particularly driven by large industrial machinery, wind turbines, and electric vehicles. Certain applications, such as wind turbines and current automotive motor designs, necessitate RE-based permanent magnets due to their strong magnetic flux capabilities in a compact volume. This renders RE-based permanent magnets indispensable elements in the foreseeable future for these applications [20]. Ferrites count with important advantages by comparison with other magnets in view of practical applications:

- Their constituent elements are abundant and cheap.
- They have reduced environmental impact in the extraction and postprocessing routes in comparison with REs.
- They are electrical insulators, therefore avoiding eddy currents (important for dynamic operating conditions such as those integrated in electrical motors).
- They are chemically inert and have practically no corrosion problems, making possible air processing, i.e., largely reducing fabrication costs.

Despite the large amount of ferrite waste generated during manufacturing, there is a lack of studies dealing with the possibility of recycling this strontium ferrite waste. There have only been studies dealing with the possibility of recycling the elemental constituents from different sources, but not the strontium ferrite material after completion of magnet manufacturing or extracting from WEEE. The aim of this study was to guarantee sustainability by demonstrating a method that can be easily and cost-efficiently applied by the authorized waste recipient to permanent magnet manufacturing plant. The prices of both the constituent elements and the processing route are very low for ferrites by comparison with those of RE - based magnets. On this basis, recovery and recycling of the WEEE generated might be interesting only from an environmental point of view but prohibitive in terms of implementation costs for a company. However, a recovery and recycling process fulfilling the following requirements will guarantee straightforward implementation in production with no economic losses but rather gains:

- The recycling process makes use of the facilities already existing in the company, i.e., avoiding the acquisition of new equipment.
- The parameters of the recycling process are comparable to those used in the processing of the strontium ferrite starting powders acquired by the company from an external supplier.
- The quality of the recycled material is not inferior to that of the starting new material, i.e., allowing its use in same applications with no negative impact on the performance of the final product.

This last point is usually one of the drawbacks pushing back implementation of a recycling process for whatever material, especially when looking at products with technological implementations, which require demanding quality control according to well-established standards. According to A. Bollero et al. (2017) the quality of the recycled ferrite powder has been tested and compared to that of the new starting ferrite material [20]. The magnetic properties of the recycled powder not only match those of the starting material acquired by the company for the production of magnets but exceed them. A coercivity value 3.5 times larger than that of the new starting ferrite powder, accompanied by a 25% increase in remanence, makes this material a new and improved ferrite product to enter the production chain in the factory with an extended applications range. This improvement is proven to be due to tuning of the morphology and microstructure through processing and subsequent heat treatment. The use of processing conditions in the same range as those typically used in the preparation of ferrite powders and magnets, in combination with the superior magnetic quality of the resulting powders, makes this method a suitable path to guarantee sustainability and an efficient use of resources in permanent magnet companies [20].

So we end up in the present where this thesis aims to *refine the process of magnetic material recovery from WEEE, facilitating its reintegration into the production cycle of permanent magnets* and is executed under the auspices of the HORIZON2020 Plooto project. This initiative aims to address the growing challenges associated with electronic waste management while simultaneously contributing to the sustainable production of critical materials for various industrial applications. This thesis explores the significance of refining the process of magnetic material recovery from WEEE and its implications for sustainable resource management and circular economy objectives. It examines current challenges and constraints in magnetic material recovery, identifies emerging technologies and best practices, and discusses future directions and opportunities for enhancing the efficiency and effectiveness of the recovery process. By advancing our understanding and capabilities in this critical area, we can contribute to the development of more sustainable and resilient supply chains for permanent magnets, thereby promoting environmental management and economic prosperity.

This thesis follows the standard structure, which means in the following chapter 2 we will present similar European Projects that have been published, followed by an extensive review of the HORIZON2020 Plooto project while chapter 3 deepens the analysis by aiming the pilot case of magnet recycling, and presents data on the recovery of magnetic material from WEEE. Additionally, this section describes in detail the functions of each company that take place in the specific network. Moving on to chapter 4, the methodology followed and the preliminary linear programming model developed to solve the pilot case problem is highlighted. In addition, the constraints and problems of the specific model were presented and finally, chapter 5 describes the general conclusions drawn and the ideas proposed for future research in order to correct the problems, address the constraints and further improve the specific case.

2 Similar EU-Projects – Description of Plooto Project EU

In 2013, the REMANENCE concept was set up. The REMANENCE concept was an ambitious project targeting to dramatically increase the amount of rare earth magnets recovered from existing waste streams. The focus was on recovering and recycling neodymium-iron-boron (NdFeB) magnets directly to a powder that could be used to produce new sintered or polymer bonded magnets, but processing of lower quality material was also undertaken to provide a source of Nd metal. Advanced sensing and mechanical separation techniques had been developed to recover these rare earth magnets from electrical and electronic equipment. These materials were then processed using hydrogen decrepitation to transform the NdFeB magnets into a hydrogenated powder. This powder could then be extracted mechanically from the obsolete devices, and could be processed further to produce either sintered or bonded rare earth magnets. The project had successfully integrated these processes into a virtual production line and had produced new magnets from hard disk drives waste. The properties of the new magnets were comparable to those made from fresh material, and the economic analysis has shown that the cost of the magnets would make them a competitive option in today’s market.

In 2019, the EU-funded SUSMAGPRO project came up with a similar purpose, to develop a pilot supply chain from recycled neodymium magnets in Europe [30]. With the support of a multinational team and new technologies developed under the FP7 REMANENCE project, the product would be tested. These novel hydrogen technologies would be used in the separation and purification process. Remanufacturing would then take place to achieve different forms of magnets and the potential of the new method will be evaluated. SUSMAGPRO introduced new ways to recycle and reuse magnets directly from waste, creating a shorter recycling loop with a higher recovery rate and increased yield (25 %) compared to traditional methods. The process begins with evaluating scrap products and thoroughly analyzing all materials. This data informs component segregation and guides recommendations for efficient recycling designs. The scrap products are then robotically disassembled, separating magnet-containing items from the waste streams using a sensor array. The resulting magnet scrap is exposed to a hydrogen atmosphere to produce powders for further processing, with or without prior thermal demagnetization. The powders are subsequently transformed into new alloys or magnets through various processes. These include an innovative technique based on metal injection moulding that involves shaping, debinding and sintering and allows creating complexly shaped magnets with minimal production waste. The newly produced magnets can then be distributed to end users for use in various applications, such as car speakers, water pumps and automotive rotors [30].

With this in mind, an innovative pilot sensing and robotic sorting line has been constructed that will locate and concentrate NdFeB-magnet-containing components by separating collected waste electrical and electronic equipment. A prototype line has been assembled and testing with moderate quantities of scrap from different WEEE sources is under way. The line was designed in a modular and transportable manner, allowing on-site segregation of magnet-containing scrap, i.e. in computer server farms.

In 2020, a new project was introduced. The innovation supported by VALOMAG concerned a technology enabling to dismantle EoL applications, for the extraction of permanent magnets and their recycling in short loop processes based on the direct reuse of hard ferromagnetic alloys for bonded magnets and sintered magnets manufacturing. VALOMAG project answered the need of the waste management sector to treat waste with magnets as no solution exists currently due to technological limitations. NdFeB based permanent magnets are indispensable for today's technology-driven society, and this dependence is likely to increase. As REE such as Nd and Dy have a substantial risk and a high commercial value, the recycling of EoL products as NdFeb magnets is a promising route to lessen the supply risk. Moreover, Life Cycle Assessment studies (LCAs) have already been performed for NdFeB magnets produced from virgin raw materials and for magnets produced using a magnet-to-magnet recycling process. The results have shown that the recycling process has significantly less environmental impact than production from raw materials with about 31% to 55%. The VALOMAG project proposed to supply a technical solution for permanent magnet disassembly of EOL applications like hard disc, electric vehicles and wind turbine and to assess two short loop recycling technologies (HD/HDDR and stripcasting) for high and medium quality magnets with a third alternative route using hydrometallurgical processes for low quality magnets.

2.1 Plooto's contribution

The World Economic Forum [11] highlights the use of traceability across the value chain as the key to accelerate the shift towards circular and resilient production processes. There are four challenges here:

A. Connecting traceability to sustainability and business objectives,
B. Deploying key enablers such as data and technology,
C. Building a collaboration ecosystem across the value chain, and
D. Taking a rapid test-and-learn approach to get started.

After gaining insights from stakeholders and processes' analyses, Plooto address these as follows:

- Resolve A: By a digital transformation framework based (i) on traceability strategies for materials/products per business case, (ii) reference processes for SRMs use from waste deposit to new products and (iii) governance models for circular value chains.
- Resolve B: By a platform of interconnected Digital Twins (DTs) based on specific standards and enhanced with cognition services (thus denoted as CDTs), enabling advanced reasoning and autonomous decision making; the trustworthy data exchange among CDTs and the material certification will be handled by RM-recovery and waste dataspaces and the CDTs output will feed product passport and balanced scorecard tools.
- Resolve C: By introducing i) from the business and operational perspective: supply chain governance models which adopt transparent rules of collaboration and supply chain structures and ii) from the digital perspective: CDT governance through federation and coordination of CDTs coupled with security and privacy registries and enhanced with collective analytics, magnifying the benefits of value chain collaboration.
- Resolve D: By deploying and testing Plooto's solutions in three exemplar scenarios, yielding replication and scaling up guidelines based on lessons learnt, plus contributing to DT standards on circularity, and educational and learning activities for the development of skilled and innovative workforce under circular principles.

This sequence of actions is typical of the Design Science Research approach in Information Systems. This approach, will evolve in Plooto to provide: A Circular and Resilient Information System (CRIS) that enables waste reduction and end-to-end traceability of SRMs through interconnected digital services for real-time decision making, monitoring and certification of materials and products, relying upon a digital transformation strategy pertinent to process industries.

Plooto analyses three industries and their supply chains to collect their circularity needs and constraints and to model the Value chain network (stakeholders' roles and input/outputs). By identifying the materials and products to be used as SRMs, Plooto will derive the replicable strategies, the key objectives, and initiatives to reduce waste across the entire chain, through reference processes for waste deposit, treatment and re-use back in the production. The framework is complemented with solid governance models (Business governance, Data storage standards for easy data access), a balanced scorecard framework ensuring the sustainability of the digital circular supply chains, and guidelines for digital passport design and certification schemes in line with the call for passports on a product level by the European Resource Efficiency Platform [15]. The framework is configurable and capable to respond to the varying supply and demand of critical RMs in different industrial processes with the goal to maximize waste reduction and optimal SRMs use across a product's life cycle. More particularly, Plooto will address the following business cases, but in the context of this thesis, only the pilot case that concerns the use of WEEE for the production of permanent magnets will be examined.

Table 4: Analysis of the Business cases, inside Plooto project

Business Cases	Industry	Materials/ products	Current State/processes	Plooto Outcome
CFRP waste for Drones	Drone manufacturer	CFRP waste, CFRP component, Drones	No DTs or digital services. A drone manufacturing process assembles CFRP Composite material products which are produced by CFRP waste (uncured scrap prepreg).	Coordinated CDTs for waste preliminary processing, production of composite material products and assembly of the latter for drones, assessing and evaluating resource losses and material waste. User tools to support certification of conformity of the expired prepreg from its first treatment by the waste owner onwards.
WEEE for Magnets	Magnets Producer	WEEE NdFeB and Sr-ferrite permanent magnets, new bonded magnets	No DTs or other digital services. A magnet production process from PM pellets, deduced through a recycling process from PMs (bonded NdFeB and Sr-Ferrite, and sintered Sr-Ferrite), recovered from scrap, e.g., electrical motors.	CDTs for WEEE processing to extract PMs, recycling of PMs, fabrication of new and re processing of disregarded bonded magnets, linking the supplier of secondary raw material with the consumer of these RMs while assessing and evaluating in real time the different steps for the recovery of PMs from WEEE with conventional methods. User tools to support the traceability certifications concerning e.g., recycling processes, circularity index, as well as outcomes and products (e.g., the origin of NdFeb PM).
Citrus processing waste for juice by products	Citrus processing plant	CPWW, CPW, d-Limonene, molasses, animal feed	No DTs or other digital services. Recovery of EO which is distilled by CPWW and CPW to produce d-Limonene and by-products with high commercial interest such as molasses and animal feed.	CDTs for EO distillation, molasses condensation, and animal feed production process from CPW, to accurately estimate products' quality characteristics, fine tuning the process conditions in real time, while minimizing raw material loss. User tools to support certified information about the origin of raw material (processed fruit) and processing steps, identify circularity effects and compliance with regulations and standards.

Specifically, Plooto will focus in increasing the reuse of NdFeB and Strontium-ferrite (Sr-ferrite) permanent magnets (PMs), recovered by WEEE from magnet products. The possibility to recover NdFeB PMs from WEEE brings many competitive advantages such as a decreased dependency on third countries for the obtention of Nd (rare earth element, i.e. critical raw material) to manufacture magnets in Europe, the obtention of a competitive secondary raw material source and the valorization and reduction of WEEE landfilled. Based on the volatile prices of rare-earths over recent years, together with improved design of devices by manufacturers making possible the substitution of NdFeB magnets by ferrites in more and more applications, Sr-Ferrite magnets have received a renewed interest by both the scientific community and industry, including magnet manufacturers and end-users from automobile, renewable energy technologies, home appliance and electronics.

2.1.1 Recycling of WEEE by FERIMET

Recycling is defined as the reprocessing of recovered materials at a product’s EoL, returning it into the value chain. The aim of recycling is to conserve raw materials by maximizing the value retention of the materials contained in a product in either its component or material form. The recycled material may be referred to as a "secondary" material, as opposed to a “primary” material that is extracted from the environment [17].

To clarify the scope of this study, it's essential to differentiate between recycling and recovery, terms frequently used interchangeably and inconsistently in the literature. Recycling involves the complete cycle of a material, from its initial production to its use, and then back to its original state or repurposing. Recovery, on the other hand, is a specific phase within the recycling process where materials are extracted from waste through sorting and separation techniques. Once these recovered materials undergo processing and refinement, they can be reintroduced into the recycling loop to create new products.

The distinction between the recycling and recovery process is shown in Figure 5. In the case of an EoL plastic bottle as an example, the recycling process includes the collection of EoL bottles to the production of a new bottle using the materials recovered from the EoL plastic bottle, the recycled product made of secondary materials. The recovery process is limited to the processing of the collected materials to recover a secondary material, which can be used to produce the recycled product.

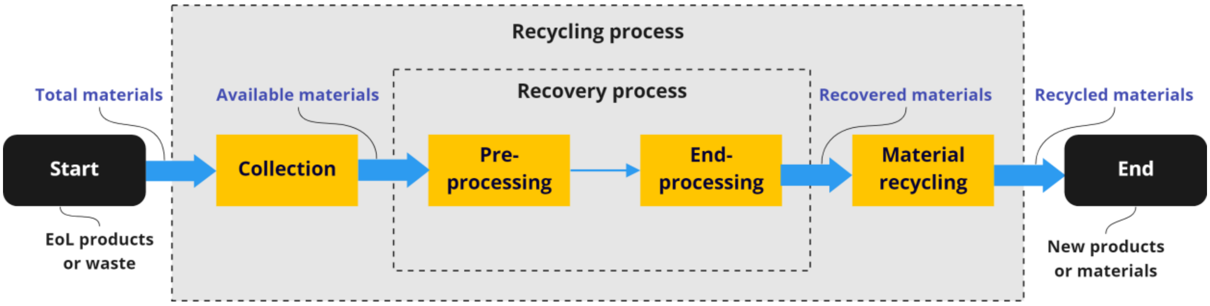


Figure 5: Overview of the material recycling and recovery process

The recovery process comprises two primary phases: pre-processing and end-processing. The pre-processing phase involves the initial disassembly and depollution of the product, during which hazardous and valuable components are removed. This phase also includes sorting, size reduction, and separation techniques. The end-processing phase occurs once the materials have been adequately separated. This phase focuses on refining the materials to a state where they can be utilized in the recycling process to create new products, a process known as material recycling.

Efficient disassembly techniques are needed for material recovery and recycling technologies to benefit from economies of scale and improve the recovery grade. This is because the quality of the recycled and recovered material is highly dependent on the degree of separation of the material. Improved disassembly could enable better separation and thus increase the value of the recovered or recycled material, while reducing refining time and costs. In the case of permanent magnet recycling, there are four options depicted in Table 5.

Table 5: Recycling options for Magnets [18]

Direct reuse	The disassembly of a permanent magnet at the EoL such that it can be utilized in its current state for another application. May need to be wiped, cleaned, re-coated or re-magnetized.
Magnet to magnet	The bulk recycling of all the materials in a permanent magnet to form a new magnet with similar properties (often lower)
Waste to alloy	The extraction of an alloy containing REEs but may not be in the desired quantities for a magnet, could be used in other applications.
Waste to element	REEs are separated back to pure metals using energy and chemically intensive processing methods such as pyro- or hydrometallurgy.

By recovering the REEs from permanent magnets, the dependence on virgin production (primary materials) can be reduced which will help overcome supply issues related to the extraction of REEs. The preferred recycling method used will depend on technical and economic feasibility, while taking environmental impacts into account. From an environmental and economic perspective, magnet to magnet and waste to alloy would be the preferable and more realistic options for the recycling of permanent magnets from WEEE. Studies have shown that the environmental impact of using recycling magnets is tremendously lower than that of virgin magnets. There are variations within the recycling processes, where the shortest and simplest route would be magnet to magnet recycling followed by waste to alloy. In this case it is assumed that the shorter the route and the simpler the process the less energy and chemical intense the process, along with lower processing costs.

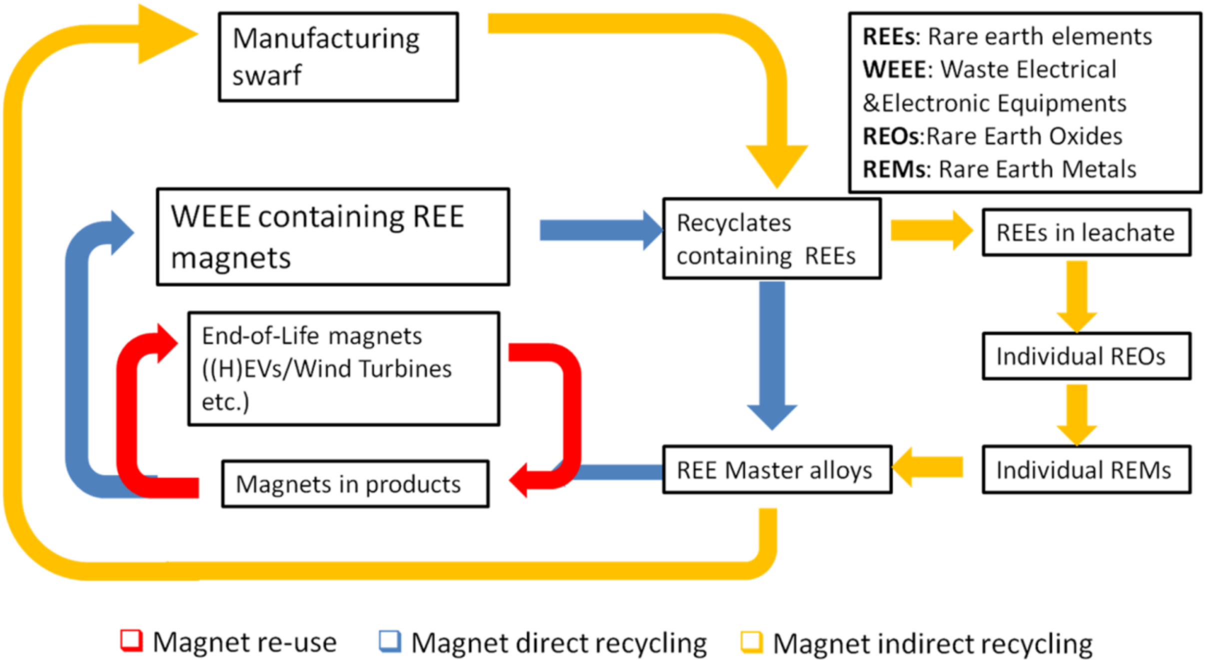


Figure 6: Indicative PFD of different recycling options for PM in WEEE

For the needs of the Plooto project, FERIMET has been appointed as the company that will undertake the collection and separation of the recoverable magnetic materials from the WEEE that will be sent for recycling. FERIMET is the Celsa Group Company dedicated to the recovery and treatment of ferrous and non-ferrous materials.

Nowadays FERIMET imports 24,8 Tn/year of WEEE where different kind of motors and magnets are found. Approximately 0.5 to 300 g PMs (either bonded NdFeB or Sr-Ferrite, or sintered Sr-Ferrite) are found in each WEEE product depending on the electrical motor or magnetic component contained in each product [19]. Nowadays the WEEE arrives mixed, and it is crumbled mixed. After this, different processes are applied to sort ferrous and non-ferrous materials.

To meet the growing demand for the production of permanent magnets and to address the resulting resource consumption and shortage, it is important to consider the recycling of WEEE so that valuable materials can be recovered. The NdFeB and Sr-ferrite magnets found in the WEEE were identified as the most important to be recycled due to the impacts associated with their extraction.

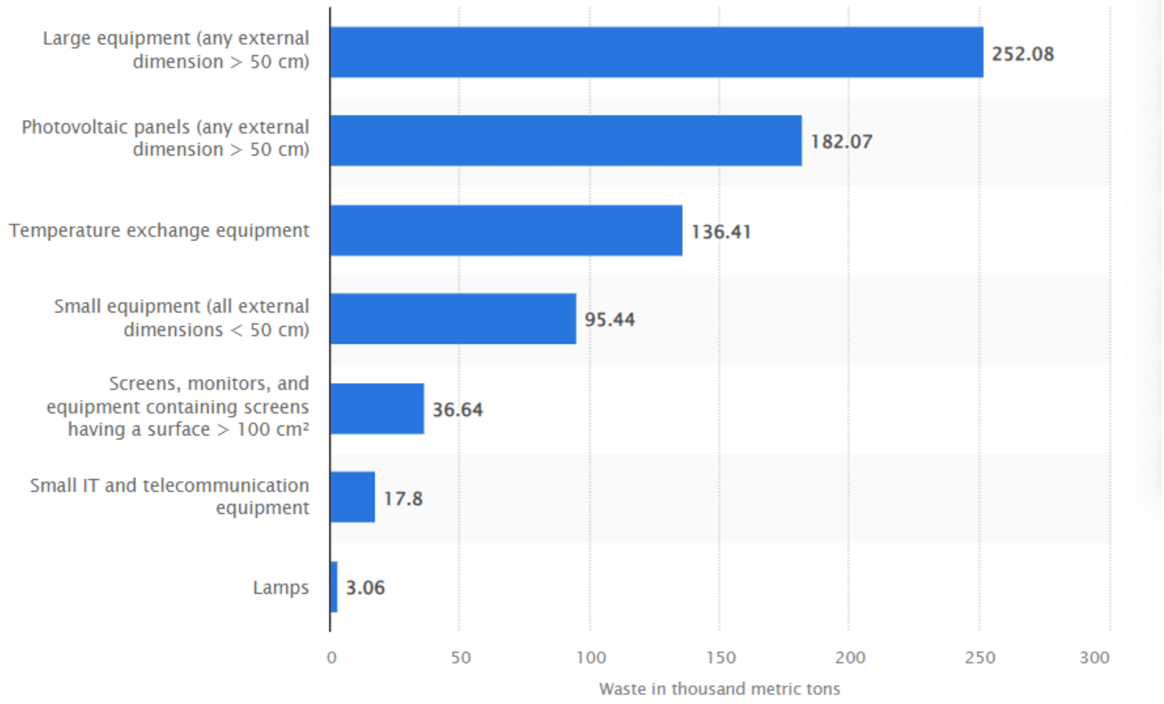


Figure 7 Minimum targets for the separate collection of WEEE in Spain in 2023, for each category

As can be seen from the above chart (*Figure 7*), the targets for WEEE collection in Spain in 2023 are high. That implies that FERIMET will be able to import more tonnes of WEEE and as a result, through a series of purification processes, to extract more magnetic material (NdFeB or Sr-Ferrite) that is critical for further processing to create secondary raw materials.

2.1.2 Re-Processing by IMDEA

However, the Nd found in the different electrical motors is currently not recovered. IMDEA comes to fill this gap. IMDEA Nanoscience is an interdisciplinary research center located in Madrid (Spain) and dedicated to the exploration of nanoscience and the development of applications of nanotechnology in connection with innovative industries. The Group of Permanent Magnets and Applications -working in Plooto- is part of the Programme Nanotechnology for Critical Raw Materials and Sustainability at IMDEA Nanoscience. This Programme focuses on the search of solutions through the application of research and innovation to the fragile economic, political and social situation faced by Europe related to the provision of raw materials of high-criticality required for a sustainable technological development.

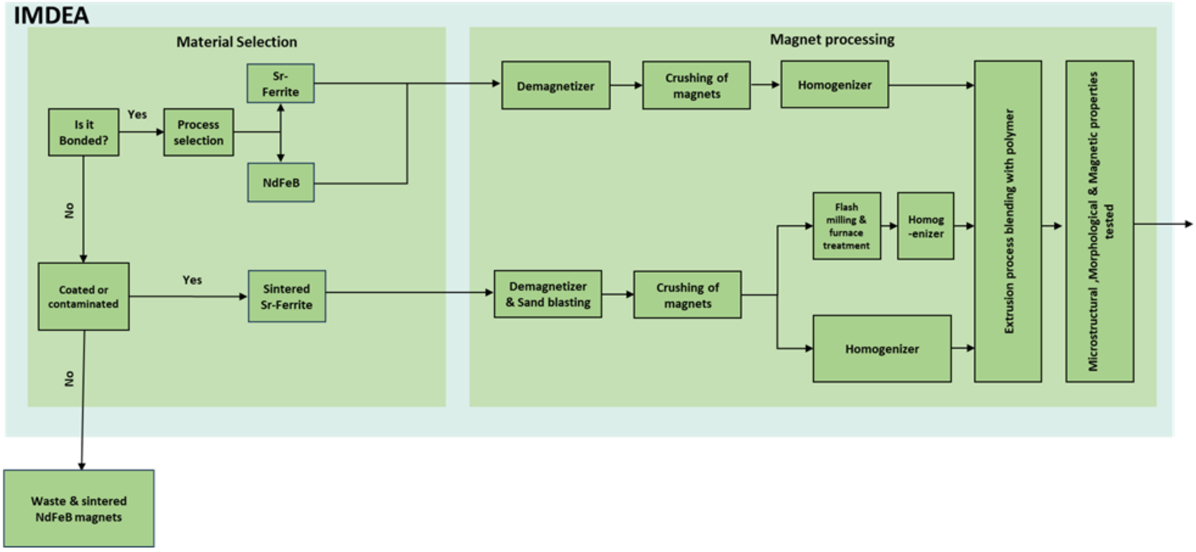


Figure 8: IMDEA Process Flow Diagram

IMDEA has developed a method for recycling permanent magnet residues resulting from the manufacture of PMs at an industrial plant [20], which allows the recycled powder to be used for the fabrication of injected magnets. Additionally, application of IMDEA's self-developed methodology (flash-milling) to ferrite recycled powder has been demonstrated to increase the PM properties well-beyond those of the brand-new-commercial powder, thus opening the possibility of fabricating an improved permanent magnet material. As for the fabrication of PM/polymer composites for injection, IMDEA has developed a state-of-the-art scalable solution-casting method, successfully applied to diverse permanent magnet materials (including NdFeB, Sr-ferrite and MnAlC) [21]. This method allows the possibility of using solution-casting in the preparation of a PM/polymer compound with a very high-load of PM content (above 90 % PM content) to be used for injection and extrusion.

The above require a) accurate and reliable data concerning composition, quantity available and cost of the recovered PM material, to increase and optimize the use of the secondary raw material in the magnets production from the magnets' producer perspective.

2.1.3 Magnets production by IMA

The third contributor to this project is IMA, which is a leading company in the magnetic sector in Spain with more than 30 years of experience. Being a worldwide magnetic supplier company, with customers from more than 60 countries. Developing technologies to improve the process of transformation, rectification, magnetization and customization of magnets. Experts in injection and overmolding of bonded materials, manufacturing industrial magnetic separator systems and electromagnets. IMA has one of the largest laboratories in Europe with high technology measuring equipment. The quality of the products is guaranteed to ensure the precision in different important sectors as automotive, aerospace, wind energy, electric motors, electronics, medicine, robotics, recycling, and mining, amongst others.

At present IMA Magnets (IMA) produces magnets for a wide range of magnetic industrial solutions using NdFeB (37 Tn/year) and Sr-ferrite (25 Tn/year) together with NdFeB and Sr-ferrite recovered from its own magnet production process via injection molding. The purpose of this specific company is to increase the import of secondary raw materials and reduce the raw material, as the cost of import from China is very high and also after experiments it was observed that the magnets produced using SRMs yielded products with improved magnetic properties. Today the usage of SRM (bonded NdFeb, Sr-Ferrite) in PM magnet pellets' production is 0 %. With Plooto Project it is estimated that the use of SRMs in the production of magnets will reach 30%.

There is a lack of recycling activities carried out nowadays by most PM manufacturers, so Plooto will open a new industrial activity by "closing the loop" (reuse of residues, leftovers and disposed magnets) and moreover extending the market of the PMs obtained through the recycling process beyond the original applications. The Plootos' success will lead Ferimet to re-consider the EoL of additional products such as those PMs (NdFeB and Sr-ferrite) coming from vehicles. This will allow an exponential growth when considering that the market of electric vehicles (that saw annual sales doubling in 2018 [22]) and PM motors account for 90% of all battery EVs in the market, assuming that in average a vehicle today is using 400 g NdFeB

PMs (120 g NdPr oxide and Dy) for utilities and accessories (these numbers without considering the large use of NdFeB magnets in the driving motor) this would result in an annual incremental demand of 120 t NdPr oxide and Dy for every 1 million vehicles sold. Considering that a car contains more than 150 permanent magnets in addition to those (the largest volume) making the driving motor, the number of permanent magnets to recycle after EoL of cars makes the biggest market of permanent magnets to recycle. IMA deals with diverse customers from the automobile sector [23].

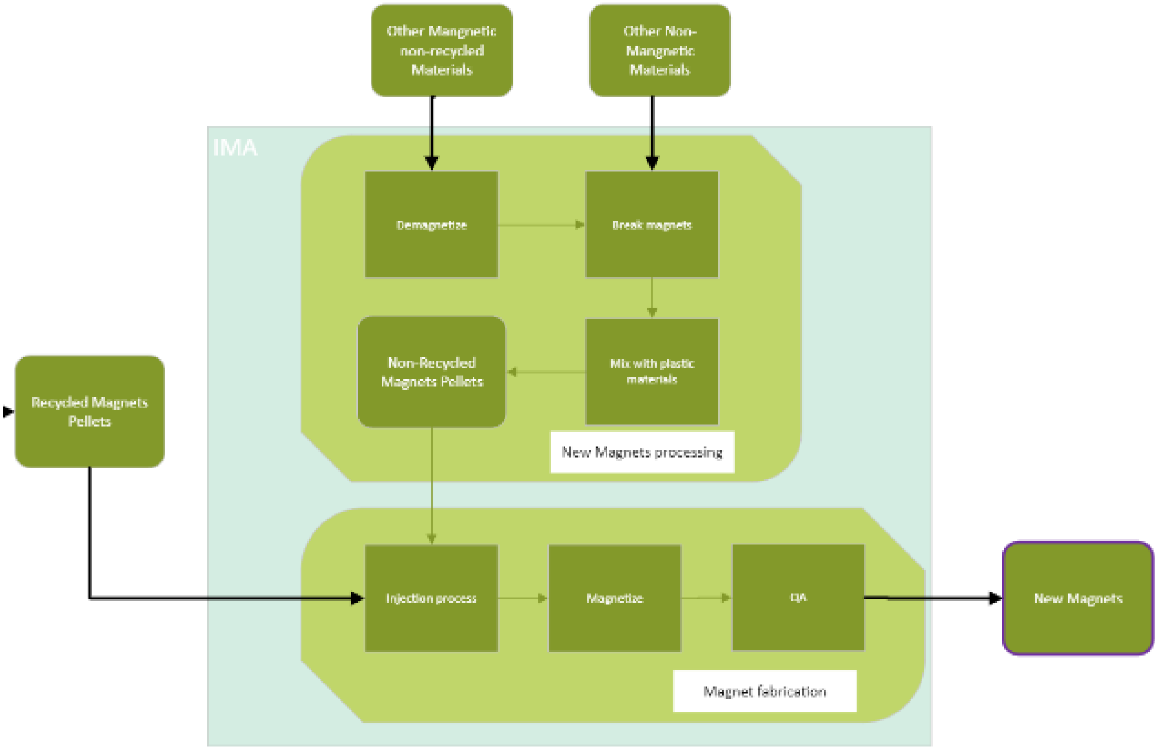


Figure 9: IMAs' production processes

2.1.4 Network Design

As waste generation by various industries is increasing at a skyrocketing pace, many governments across the globe compel the producer/manufacturer to implement the extended producer responsibility (EPR) principle. According to the Organization for Economic Cooperation and Development (OECD), ‘’EPR is a policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products’’. With this instrument, manufacturers now must develop a sustainable reverse supply chain (RSC) besides the conventional forward logistics (FL) system. According to Stevens (1989), a forward supply chain (FSC) is a system consisting of material suppliers, production facilities, distribution services, and customers who are all linked together via the downstream feed-forward flow of materials (deliveries) and the upstream feedback flow of information (orders). On the other hand, when the FSC and RSC systems are considered in an integrated manner, the concept of the closed-loop supply chain (CLSC) evolved. It considers efficient product return management and conducts value recovery activities so that secondary materials can be used as input for “new” customer product. Rather considering legal, social responsibilities, or even operational and technical details of the FSC and RSC, the CLSC focuses explicitly on business perspectives of the supply chains. According to Guide and Van Wassenhove (2009), CLSC management is the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time. From the sustainability viewpoint in all three dimensions – social, economic, and environmental - in conjunction with the circular economy, RL/CLSC is an emerging area of research that attracts both academic and industry practitioners [20].

Network design with CLSC refers to transforming a supply chain into a closed-loop entity by forming a direct and coordinated relationship between FL activities (i.e. material processing, manufacturing, and distribution) and tasks associated with RSC.

Kannan et al. (2010) developed a mathematical model using LP considering a multi-echelon, multi-period, multi-product CLSC network with a focus on cost reduction, for making decisions in the material procurement, distribution, recycling and disposal of waste batteries. Chouinard et al. (2008) proposed a stochastic programming model to design a CLSC network considering location specific network-design decisions such as recovery and demand volumes with respect to capacity constraints and operating costs [20].

A significant area of research in the Reverse Logistics (RL) and Closed-Loop Supply Chain (CLSC) of Waste Electrical and Electronic Equipment (WEEE) revolves around decision-making and performance assessment of RL/CLSC processes and networks, including transportation. Researchers investigate the economic and environmental performance of organizations and businesses engaged in WEEE management.

Key RL/CLSC processes include product acquisition, collection, inspection, sorting, and disposition. Disposition options encompass recycling, reuse, repair, remanufacturing, and disposal. Studying these processes aids in optimizing the efficiency and sustainability of WEEE management practices.

In our research we can consider our instance as a closed loop, as we expect full cooperation between the three companies as one unit, which will provide all the services mentioned above.

3 Total Network - Supply Chain

In this section of this thesis, the entire production process that will be followed by all three companies participating in the Plooto Project, as well as the mathematical model for flow optimization for the overall process will be presented. *Figure 10* shows the overall flowchart of the project.

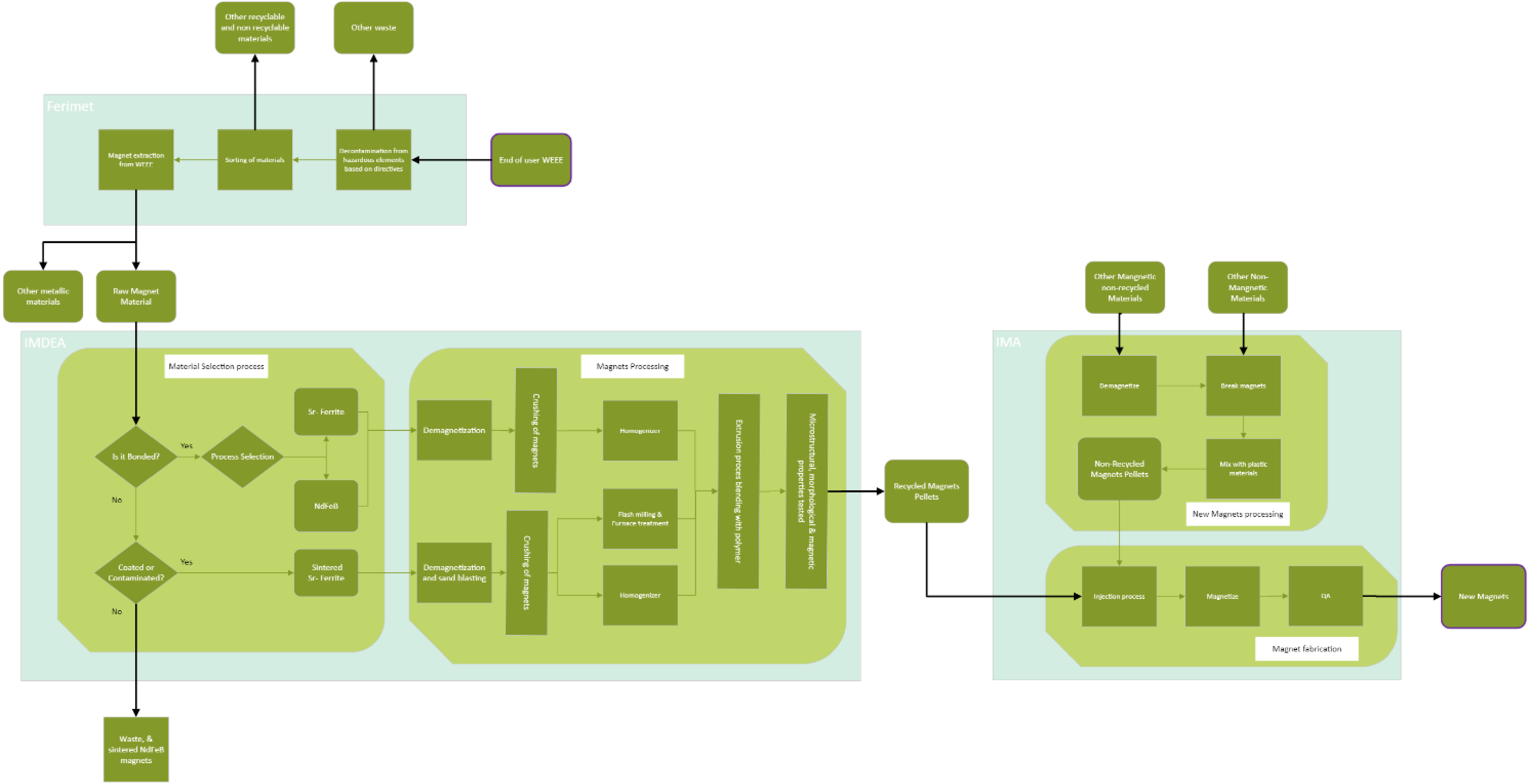


Figure 10: Overall Process Flow Diagram

Figure 11: Different types of WEEE

As can be seen from the above diagram, the beginning of the overall process starts with the collection of WEEE by Ferimet. This pilot begins with Ferimet that receives/collects appliances and devices to be dismantled from green/recycling points. Ferimet is in charge not only to dismantle and recycle the metallic parts of appliances and devices (outside the Plooto's scope), but also to recover the magnets present in the motors or engines of these appliances. This process is done mostly manually, with employees detaching magnets from the designated location. The collection and transportation of waste will be carried out using Ferimet's equipment, people and responsibility, or through reputable subcontractors who have the licenses and credentials to place this hazardous waste at the company's facilities.

Once the waste has been received and categorized, the first process that takes place is the decontamination of hazardous materials - elements, in accordance with European directives. This treatment can include a variety of processes which will not be studied in this research as data from the parent company is not yet available.

What is certain, however, is that there will be waste from this process (other waste, as shown in the diagram), while the remaining stream will proceed as an input to the materials sorting process. At this stage the waste will essentially be classified into the six categories of WEEE mentioned earlier, according to the specifications of the European directives. This process, however, will be carried out manually by the experienced staff of the company, and at the same time with the use of special tools that will be able to lift and transport waste of large volume and weight (e.g. refrigerator, freezer oven, etc.). But this stage will also result in some recyclable and non-recyclable materials that have been placed either by mistake or are not required further in the production process.

The resulting stream from this stage will proceed as an input to the final stage of Ferimet which is the extraction of the magnetic material (NdFeB or Sr-ferrite) from the waste. In more detail, WEEE processing Cognitive Digital Twin (CDT) will select the more profitable components/equipment from WEEE to extract magnets, assessing different options e.g., the use of Hyperspectral Cameras or the use of magnetic sensors that can identify which components content magnetic materials. Once the potential WEEE component is selected, WEEE processing CDT will support the extraction of the magnetic component from its housing. Motors and magnetic components can be found in many ways in many different electrical and electronic equipment. Different automation strategies will be evaluated with available technology for a mechanical process to extract the magnets for various types of electrical and electronic equipment, and once the magnetic element is accessible, its composition in Ferrite and NdFeB PMs will be evaluated and both will be recovered separately and once the NdFeB element is recovered, then these materials will be sent to IMDEA for further processing, as Raw Material Magnet.

After this, IMDEA starts to process the magnets extracted and received by Ferimet. The constraint of IMDEA is that as a research institute their ability to process magnets is constrained to 1kg per week. IMDEA is entitled to sort end-of-life magnets according to different grades of strontium ferrite and NdFeB (magnetic properties are recorded). Once the material is transferred to IMDEA's facilities, a series of processes will take place that are placed in the first stage of the production process by IMDEA, called the Material Selection Process. At this point, through the data provided by the company, the analytics department will determine the type of each material. As shown in the diagram, it will be possible to distinguish between bonded materials, coated materials and contaminated materials. Initially the bonded materials will be separated, through a specific company process (for which there is no documented data), into NdFeB magnetic material and Sr-Ferrite as they are expected to coexist in this category of materials. Then the materials that are not bonded will be either coated or contaminated. For coated materials (such as for example materials with slag or a non-contaminated material) as shown above, they will be separated by a similar process to the previous one, which as expected from the data of the research so far, will yield sintered Sr-ferrite. However, a proportion of the input is expected to be contaminated, which will be extracted from the production process and sent for hazardous waste management by a specialized company, which will take it for recovery (if possible) or disposal in a landfill.

Once the materials have been separated, they will pass to the second stage of IMDEA's production process called Magnets Processing. The NdFeB and Sr-ferrites from the bonded materials will first be thermally demagnetized. The conditions in the

Figure 12: Demagnetization equipment

demagnetizer will depend on the type of magnet, its shape and size as well as the magnet grade. This suggests that we can expect different temperatures and waiting times of the materials depending on the case. This treatment takes place so that there are no problems in subsequent processes (such as magnets getting stuck inside the equipment, rendering it unusable). The effluent then enters the crusher so that all the diverse pieces of magnets are crushed to a crude form of small particles or powder before passing to the homogenization stage.

The working principle of a homogenizer is that by passing coarse or large particles through a narrow orifice under high pressure, the large particles can be converted into fine particles. Homogenizers work on the principles of shearing, cavitation, and turbulence. Obviously, the goal of the homogenizer in this process is to be able to extract particles of magnetic material in a specific particle size, which requires specific (currently unknown) conditions.

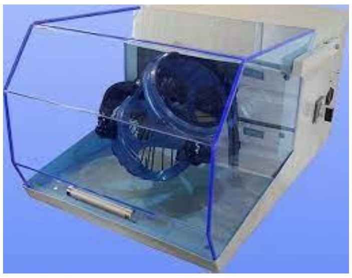


Figure 13: Homogenizer

On the other hand, we now have sintered Sr-ferrite, which is also coated with some material. The same process is repeated except that the coating is first cleaned by sandblasting until the pure material remains. After the material is placed in a crusher, the material flow is divided into two alternative processes, where either the material is placed directly into a homogenizer and the above process is repeated, or flash milling and furnace treatment will take place. Finally, all the materials obtained from the processing so far will be placed in an extruder where they will be blended with a suitable polymer. Of course, it is worth noting that the type of material used and from which process it is derived will depend directly on the demand of IMA, as the magnetic properties and quality of the produced magnets may be satisfied by a specific secondary raw material, or a combination of these. Before the magnetic pellets is supplied to IMA for injection moulding, its quality will be checked on a sample basis in terms of morphology, microstructure and properties.

The third and final stage of this modern model comes and ends with the IMA production process, which is relatively simple. First of all, the materials are selected, which are divided into other magnetic non-recycled materials (OMnRM) and other non-magnetic materials (OnMM) (e.g. Bonded magnets, sintered Rare Earths, Rubber, Ferrites). The production process starts with the demagnetisation of the OMnRM, while the effluent is fed together with the OnMM into an industrial crusher at unknown proportions, in order to be transformed to powder. The powder is then mixed with polymeric materials in unknown (at present) proportions and fed into an extruder to produce new magnetic pellets. The new material is then put together with the secondary feedstock from IMDEA, so that the mixture is placed as input to the injection process. Through this process the different shapes of magnets are produced but in order to become "functional" they must first pass through the penultimate stage of magnetization. It should be noted that this is not a specific process, as different polarizations need different coils which together with various aforementioned, make the overall process batch operation.

4 Methodology

4.1 The Case Study – Methodology & LP Model

The pilot case involves, implementation of innovative technologies and processes to recover magnetic materials from WEEE efficiently. The special focus includes NdFeB and Sr-Ferrite, which are essential components in the manufacturing of high-performance permanent magnets used in electric vehicles, renewable energy systems, consumer electronics, and other advanced technologies. In order to run the pilot project, three different companies (Ferimet, IMDEA, and IMA) will cooperate to cover the demand for new permanent magnets using recycled magnets. With this in mind within the scope of this thesis, the following synthetic data were created according to discussions that took place to enable the specific mathematical optimization model to run. We have entered several data as input. Initially the energy cost for magnet extraction is the same for each category of WEEE. This means that the same amount of energy is required to extract the same amount of magnet (Sr-Ferrite or NdFeB) per type of WEEE. With this in mind, the energy costs (money units/tn) are listed in the table below:

Table 6: Energy Costs for Xij (Money Units/kg)

j i	1	2	3	4
1	9	9	9	9
2	12	12	12	12
3	13	13	13	13
5	8	8	8	8
5	11	11	11	11
6	10	10	10	10

In addition, after a thorough review conducted considering published articles, the following percentages of magnetic materials content of WEEE for each category of waste were extracted. These percentages are particularly useful as they play a key role in determining the amount of magnets to be recycled and towards the creation of new secondary raw materials.

Table 7: Proportions of each magnet components inside each WEEE type (a_{ij} %)

j i	1	2	3	4
1	0.1	0.2	0.25	0.3
2	0.2	0.1	0.2	0.6
3	0.1	0.3	0.1	0.6
5	0.25	0.2	0.1	0.25
5	0.3	0.1	0.2	0.15
6	0.1	0.2	0.15	0.4

Ferimet is the company that collects the waste electrical and electronic equipment from various points (hubs) pointed by the State and then follow the dismantling and decontamination procedures (if necessary) mentioned in a previous chapter (e.g. Direct reuse, Magnet to magnet, Waste to alloy, Waste to element). It is worth noting that currently, the employees manually disassemble the engines/motors from machines or devices and then magnets from engines/motors.

Table 8: Data regarding the Capacity for each type of WEEE that Ferimet can accept and process inside their facility (Cap_j in kg)

	WEEE type 1	WEEE type 2	WEEE type 3	WEEE type 4	WEEE type 5	WEEE type 6
Ferimets' Capacity	100	90	70	110	60	100

Very important is the parameter concerning the production of secondary raw materials. In fact, the entire implementation of the Plooto programme is based on the principles of circularity and the re-use of waste to produce high value-added products. In this particular case, and for the purposes set out in the proposal for this programme by the interested parties, it is essential that the final demand for the products (magnets) should be met mainly by secondary raw materials. However, this approach is quite general and vague. For this reason, and in the context of this thesis, it was assumed that the demand for magnets will be covered by a minimum percentage of 35 % by secondary raw materials. Additionally, as mentioned earlier the constraint for IMDEA is that as a research institute their ability to process magnets is constrained to 1kg per week for magnets each. This means that it has an annual production capacity of no more than 52 kg of magnets each.

Regarding the final demand for magnets, this is a parameter which the third company in this chain, IMA, has to determine. IMA still faces minor but daily challenges related to the effective production of magnets such as the creation of magnets that fits customers exact requirements and applications purposes (shape, size, weight). With this in mind and due to the fact that the company cannot predict its demand for magnets, synthetic data were used. The demand was set to 100 kg of each magnet per year.

Finally, for the purposes of the study it is not meaningful to talk about maximum capacity regarding IMA's operations, because their production process is already in place and what they wish to diversify is the import of secondary raw material. But an important factor to mention at this point is the unit purchase cost of the two different magnets that IMA currently imports from abroad to meet its production. Unfortunately, these data are not available at the time of writing the thesis, so it was considered that the unit cost for both magnets (Sr-Ferrite and NdFeb, respectively) is 60 €/kg (including all the transport costs, the exporting the raw material costs and delivering the finished product to the headquarters of the company in Spain). By using these data we solved the corresponding liner program using excel solver.

Since our research focuses on the optimization of the selection of suitable WEEE to be recycled for the production of magnetic material, certain assumptions have to be made in order to exclude minor elements and focus on those aspects of primary interest.

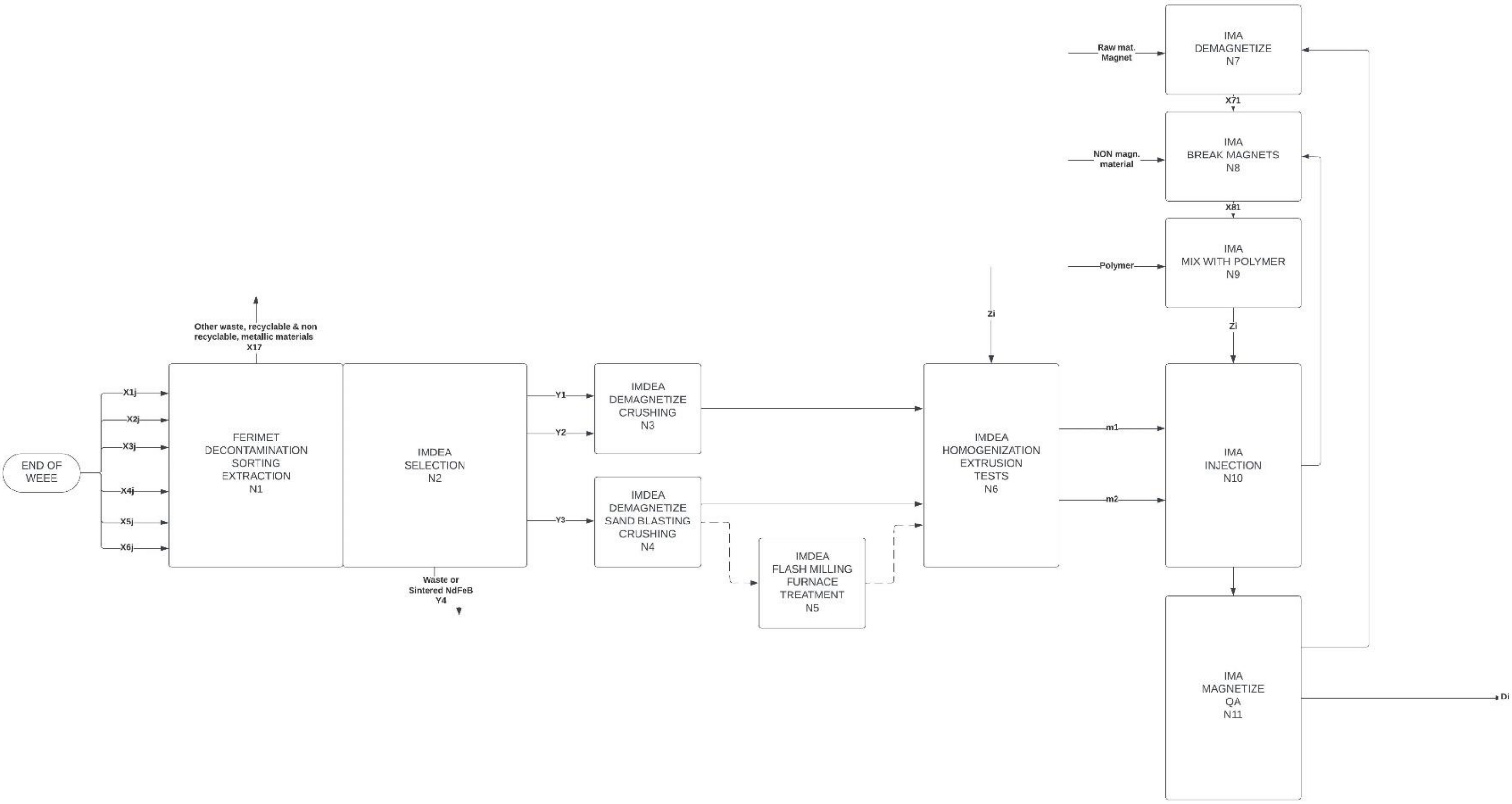


Figure 14: Proposed total Network for optimization

- All parameters used in the model are deterministic and known in advance.
- The demand for each type of magnet is known in advance.
- The energy cost for each magnet recovered per WEEE is fixed and known.
- WEEE treatment times are not considered in this model
- The quantities of output types recovered from different items of the same WEEE (Percentages of magnetic content, %) group are known and given in advance.
- The costs of operating equipment, human resources and all operational costs are assumed to be available at all times, known and incorporated in the energy costs mentioned above.
- Transport times and costs are not considered.

Based on the assumptions given, a LP formulation to optimize the WEEE recycling operation was developed. The model leads to the determination of the minimum energy consumption for the production of a given quantity of magnets determined by customer demand, within the framework of the optimal design strategy.

Table 9: Notation Summary

Notation	**Description**
Sets	
W	set of different types of WEEE
R	set of different intermediate products produced by different types of WEEE e.g. Sr-Ferrite (both sintered and bonded) & NdFeB (bonded)
M	set of different types of magnets (Sr-Ferrite, NdFeB)
Parameters	
D_i	demand for magnet $i \in M$
Cap_i	capacity of WEEE $i \in W$
$CapIMDEA_i$	Annual capacity of IMDEA that equals to 52 kg per magnet produced $i \in M$
C_{ij}	energy cost for extracting raw magnetic material $j \in R$ from WEEE $i \in W$
a_{ij}	percentage of magnet content $j \in R$ in WEEE $i \in W$
rc_i	raw magnetic material cost $i \in M$
Variables	
x_{ij}	amount of WEEE type $i \in W$ in order to produce raw magnetic material $j \in R$
y_j	amount of intermediate products $j \in R$
m_i	amount of magnets $i \in M$
z_i	amount of raw magnets $i \in M$

Minimize $C_{ij}x_{ij} + rc_i z_i$ (1)

Subject to:

$$y_j = \sum_{i}^{W} x_{ij}\, a_{ij} \quad \forall j \in R \quad (2)$$

$$m_i + z_i \geq D_i \quad \forall i \in M \quad (3)$$

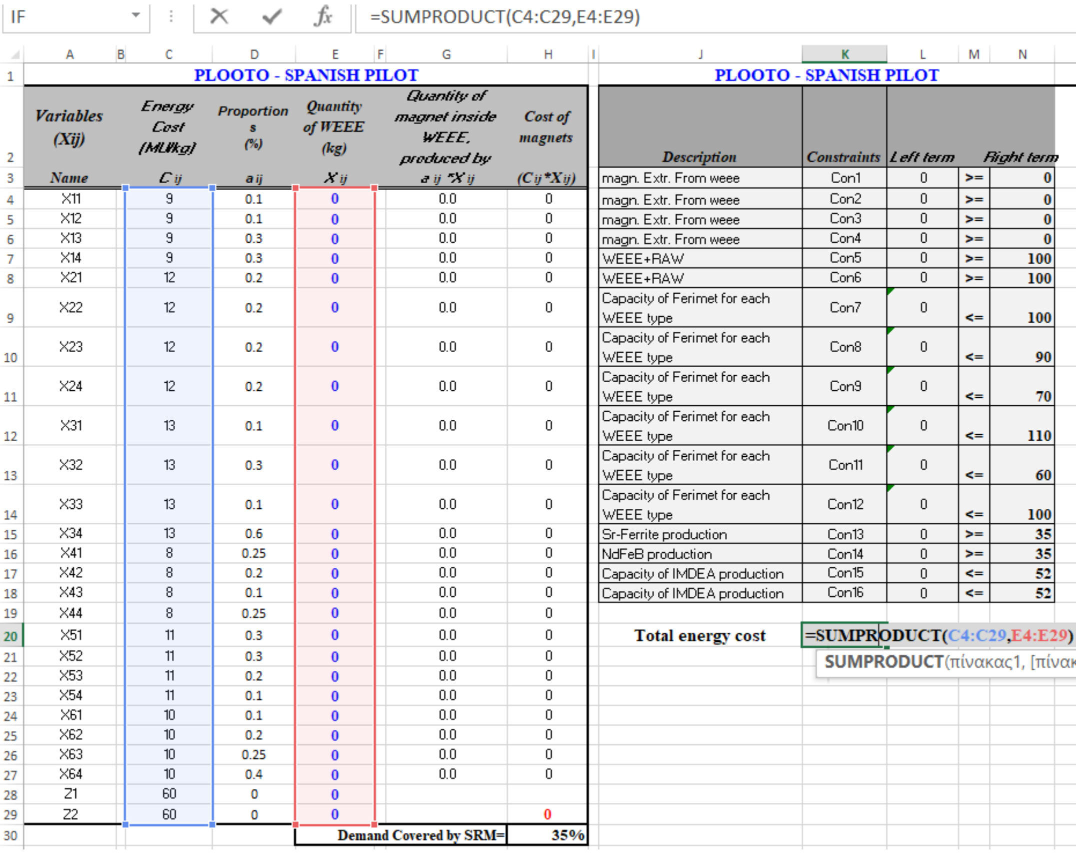
$$\sum_{j}^{R} x_{ij} \leq Cap_i \quad \forall i \in W \quad (4)$$

$$m_i = \sum_{i}^{W} y_i \quad \forall i \in M \quad (5)$$

$$m_i \leq CapIMDEA_\imath \quad \forall i \in M \quad (6)$$

$$x_{ij}, y_j, m_i, z_i, \geq 0 \qquad (7)$$

The objective function given in (1) implements the scope of the Spanish pilot which aims to minimize the total cost of fulfilling the magnet demand. The set of constraints (2) establish a link between the amounts of each type of WEEE we use with the corresponding amount of intermediate raw magnetic material we can obtain given the magnetic content of each type of WEEE. Constraint (3) dictates that the quantity of magnets produced by WEEE plus the raw magnets injection should fulfill the demand. The set of constraints (4) ensures that the amount of WEEE we use to extract the raw magnetic materials cannot exceed the total capacity of the specific WEEE. The following set of constraints (5) refers to the grouping of various secondary magnetic raw materials into magnets. The last set of constraints (6) refers to the fact that IMDEA cannot produce 52 kg of each magnet per year, as the company is still at the laboratory level, it can produce a maximum of 1 kg of each type of magnet per week. This means that for 52 weeks per year IMDEA will have the capacity to produce a maximum of 52 kg of each magnet.



=SUMPRODUCT(C4:C29,E4:E29)

PLOOTO - SPANISH PILOT

Variables (Xij) Name	Energy Cost (MU/kg) Cij	Proportions (%) aij	Quantity of WEEE (kg) Xij	Quantity of magnet inside WEEE, produced by aij *Xij	Cost of magnets (Cij*Xij)
X11	9	0.1	0	0.0	0
X12	9	0.1	0	0.0	0
X13	9	0.3	0	0.0	0
X14	9	0.3	0	0.0	0
X21	12	0.2	0	0.0	0
X22	12	0.2	0	0.0	0
X23	12	0.2	0	0.0	0
X24	12	0.2	0	0.0	0
X31	13	0.1	0	0.0	0
X32	13	0.3	0	0.0	0
X33	13	0.1	0	0.0	0
X34	13	0.6	0	0.0	0
X41	8	0.25	0	0.0	0
X42	8	0.2	0	0.0	0
X43	8	0.1	0	0.0	0
X44	8	0.25	0	0.0	0
X51	11	0.3	0	0.0	0
X52	11	0.3	0	0.0	0
X53	11	0.2	0	0.0	0
X54	11	0.1	0	0.0	0
X61	10	0.1	0	0.0	0
X62	10	0.2	0	0.0	0
X63	10	0.25	0	0.0	0
X64	10	0.4	0	0.0	0
Z1	60	0	0		
Z2	60	0	0		0
				Demand Covered by SRM=	35%

PLOOTO - SPANISH PILOT

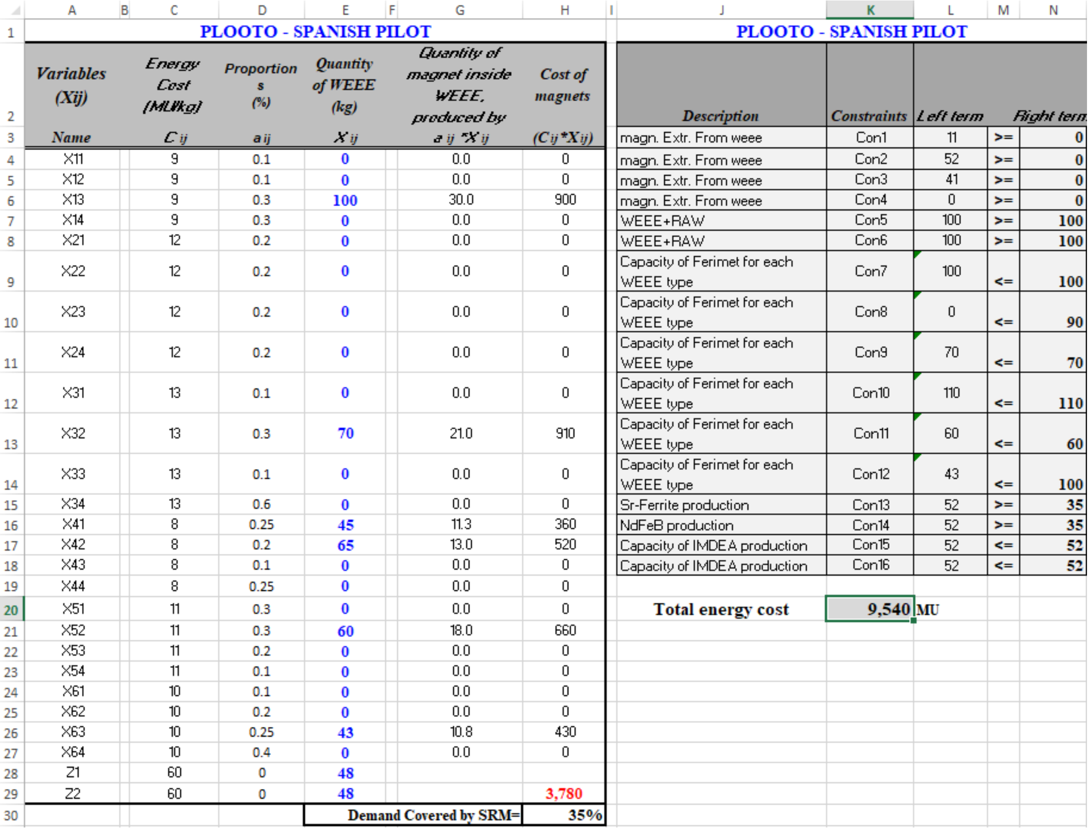
Description	Constraints	Left term		Right term
magn. Extr. From weee	Con1	0	>=	0
magn. Extr. From weee	Con2	0	>=	0
magn. Extr. From weee	Con3	0	>=	0
magn. Extr. From weee	Con4	0	>=	0
WEEE+RAW	Con5	0	>=	100
WEEE+RAW	Con6	0	>=	100
Capacity of Ferimet for each WEEE type	Con7	0	<=	100
Capacity of Ferimet for each WEEE type	Con8	0	<=	90
Capacity of Ferimet for each WEEE type	Con9	0	<=	70
Capacity of Ferimet for each WEEE type	Con10	0	<=	110
Capacity of Ferimet for each WEEE type	Con11	0	<=	60
Capacity of Ferimet for each WEEE type	Con12	0	<=	100
Sr-Ferrite production	Con13	0	>=	35
NdFeB production	Con14	0	>=	35
Capacity of IMDEA production	Con15	0	<=	52
Capacity of IMDEA production	Con16	0	<=	52

Total energy cost =SUMPRODUCT(C4:C29,E4:E29)

Figure 15: Full specification of the optimization model and the objective function

4.2 Results and Discussion

In Figure 15 it becomes apparent, how the objective function will work. As we said before, the objective function consists of two terms. The first term is the summary of the energy costs per multiplied by the amount of WEEE to be used per category. The second term consists of the cost of purchasing magnet raw material from IMA, multiplied by the quantity of raw material for each category of magnets to be used. The resulting solution is given in figure 16.



PLOOTO - SPANISH PILOT

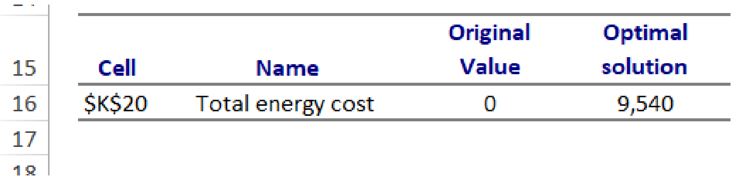
Variables (Xij)	Energy Cost (MU/kg)	Proportions (%)	Quantity of WEEE (kg)	Quantity of magnet inside WEEE, produced by	Cost of magnets
Name	C_{ij}	a_{ij}	X_{ij}	$a_{ij} * X_{ij}$	$(C_{ij} * X_{ij})$
X11	9	0.1	0	0.0	0
X12	9	0.1	0	0.0	0
X13	9	0.3	100	30.0	900
X14	9	0.3	0	0.0	0
X21	12	0.2	0	0.0	0
X22	12	0.2	0	0.0	0
X23	12	0.2	0	0.0	0
X24	12	0.2	0	0.0	0
X31	13	0.1	0	0.0	0
X32	13	0.3	70	21.0	910
X33	13	0.1	0	0.0	0
X34	13	0.6	0	0.0	0
X41	8	0.25	45	11.3	360
X42	8	0.2	65	13.0	520
X43	8	0.1	0	0.0	0
X44	8	0.25	0	0.0	0
X51	11	0.3	0	0.0	0
X52	11	0.3	60	18.0	660
X53	11	0.2	0	0.0	0
X54	11	0.1	0	0.0	0
X61	10	0.1	0	0.0	0
X62	10	0.2	0	0.0	0
X63	10	0.25	43	10.8	430
X64	10	0.4	0	0.0	0
Z1	60	0	48		
Z2	60	0	48		3,780
			Demand Covered by SRM=		35%

PLOOTO - SPANISH PILOT

Description	Constraints	Left term		Right term
magn. Extr. From weee	Con1	11	>=	0
magn. Extr. From weee	Con2	52	>=	0
magn. Extr. From weee	Con3	41	>=	0
magn. Extr. From weee	Con4	0	>=	0
WEEE+RAW	Con5	100	>=	100
WEEE+RAW	Con6	100	>=	100
Capacity of Ferimet for each WEEE type	Con7	100	<=	100
Capacity of Ferimet for each WEEE type	Con8	0	<=	90
Capacity of Ferimet for each WEEE type	Con9	70	<=	70
Capacity of Ferimet for each WEEE type	Con10	110	<=	110
Capacity of Ferimet for each WEEE type	Con11	60	<=	60
Capacity of Ferimet for each WEEE type	Con12	43	<=	100
Sr-Ferrite production	Con13	52	>=	35
NdFeB production	Con14	52	>=	35
Capacity of IMDEA production	Con15	52	<=	52
Capacity of IMDEA production	Con16	52	<=	52

Total energy cost 9,540 MU

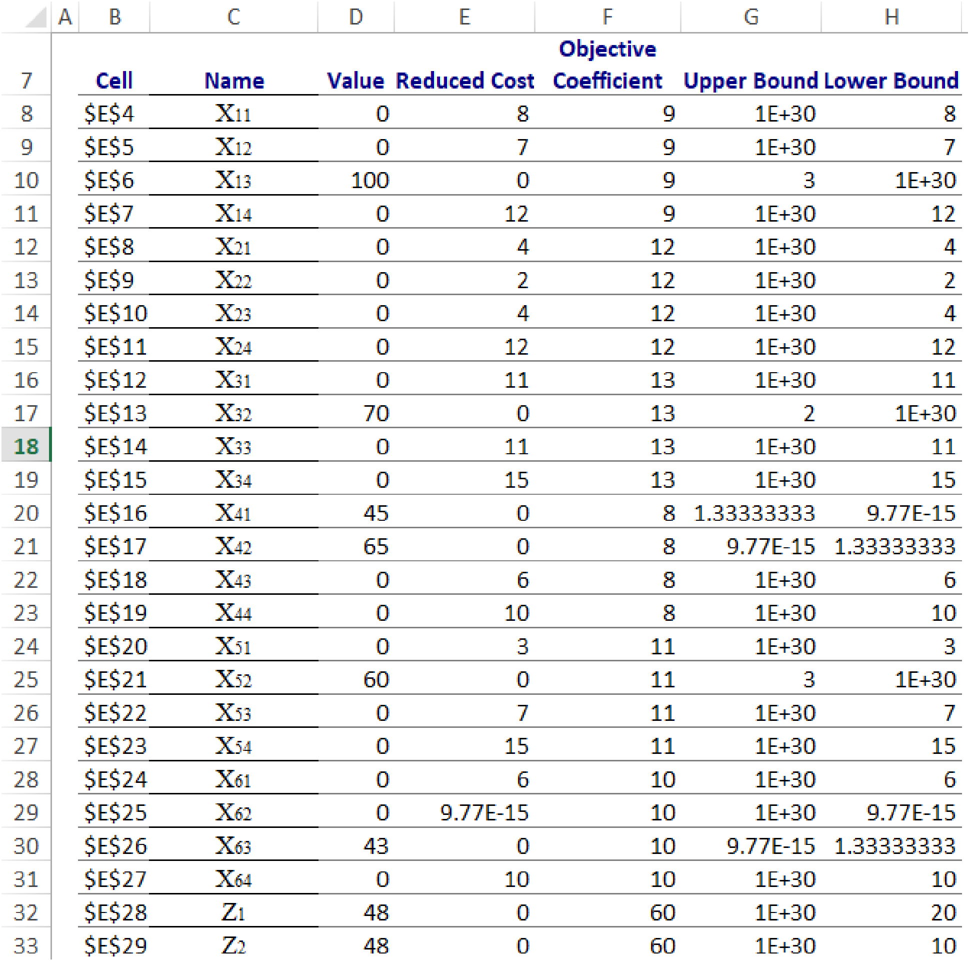
Figure 16: Model solution



Cell	Name	Original Value	Optimal solution
K20	Total energy cost	0	9,540

Figure 17: Objective function solution

As can be seen the problem was solved using the SIMPLEX LP algorithm. Using the simplex algorithm, we derived the optimal solution given in the above figure. The value of the objective function was calculated at 9.540 money units. However, this quantitative result has a degree of uncertainty, because most of the data was based on assumptions made due to a lack of data from the relevant partners.



7	Cell	Name	Value	Reduced Cost	Objective Coefficient	Upper Bound	Lower Bound
8	E4	X_{11}	0	8	9	1E+30	8
9	E5	X_{12}	0	7	9	1E+30	7
10	E6	X_{13}	100	0	9	3	1E+30
11	E7	X_{14}	0	12	9	1E+30	12
12	E8	X_{21}	0	4	12	1E+30	4
13	E9	X_{22}	0	2	12	1E+30	2
14	E10	X_{23}	0	4	12	1E+30	4
15	E11	X_{24}	0	12	12	1E+30	12
16	E12	X_{31}	0	11	13	1E+30	11
17	E13	X_{32}	70	0	13	2	1E+30
18	E14	X_{33}	0	11	13	1E+30	11
19	E15	X_{34}	0	15	13	1E+30	15
20	E16	X_{41}	45	0	8	1.33333333	9.77E-15
21	E17	X_{42}	65	0	8	9.77E-15	1.33333333
22	E18	X_{43}	0	6	8	1E+30	6
23	E19	X_{44}	0	10	8	1E+30	10
24	E20	X_{51}	0	3	11	1E+30	3
25	E21	X_{52}	60	0	11	3	1E+30
26	E22	X_{53}	0	7	11	1E+30	7
27	E23	X_{54}	0	15	11	1E+30	15
28	E24	X_{61}	0	6	10	1E+30	6
29	E25	X_{62}	0	9.77E-15	10	1E+30	9.77E-15
30	E26	X_{63}	43	0	10	9.77E-15	1.33333333
31	E27	X_{64}	0	10	10	1E+30	10
32	E28	Z_1	48	0	60	1E+30	20
33	E29	Z_2	48	0	60	1E+30	10

Figure 18: Sensitivity analysis

From the solution of the model, the above sensitivity analysis was generated and it is explained starting from the variables of the model. The first variable, X_{11}, with an objective coefficient of 9 and a recovery rate of 0.1 %, we see that has zero value and is not utilized at all towards the production of bonded Sr-Ferrite and correspondingly in the final Sr-Ferrite produced. This, as with many other zero variables discussed below, is attributed to the very low magnet recovery rate and the high energy cost, compared to other variables contributing to the production of this specific magnet. As illustrated in Figure 18, this variable has a reduced cost of 8, indicating that to derive any benefit from its utilization, its objective coefficient would need to be reduced by at least 8 units. However, conversely, even if the objective coefficient of this variable were increased, it is logical to expect that the quantity of WEEE offered would not be utilized at all.

Similar to the one mentioned above, the variable X_{12} does not contribute to the production of bonded NdFeB from WEEE type 1. With an objective coefficient of 9 and a recovery rate of 0.1%, it is observed that the existing quantity of these WEEE is not used at all, as it is obviously not profitable for similar reasons mentioned in the preceding paragraph. This variable has a reduced cost of 7, which means that in order to derive any benefit from its utilization, its objective coefficient would need to be reduced by at least 7 points.

Upon examining variable X_{13}, we observe that 100 kg of WEEE are used to produce Sintered Sr-Ferrite, precisely at the limit of Constraint 7, which pertains to the capacity for WEEE type 1. This leaves no room to utilize WEEE of the same category for the production of other magnets. With an objective factor of 9 and a recovery rate of 0.3%, the production of 30 kg of Sintered Sr-Ferrite magnet is achieved at a total cost of 900 money units. Obviously, we can see that since this variable has a non-zero value, it has no reduced cost. However, it is observed that the permissible increase is equal to 3 units (e.g. 3 units, from 9 to 12). This implies that if the energy cost increases up to 3 units, then the utilization of the 100 kg WEEE of this category will remain constant, but obviously with a higher total energy cost. However, for each unit above this threshold (e.g., 4 units, from 9 to 13), it is uncertain whether the problem will yield a feasible solution. Conversely, it is evident that the allowable reduction is infinite at this point. This indicates that regardless of how much energy costs decrease, the production quantity for that variable will remain unchanged.

The next variable relates to the production of waste or Sintered NdFeb that is not usable for Plooto purposes and therefore variables X_{14}, X_{24}, X_{34}, X_{44}, X_{54} and X_{64} have zero value. In reality, there is some level of production for these streams. However, for this project, these quantities are considered insignificant and were assumed to play no role in contributing to the final product, for this project. Therefore, they are treated as zero. Nevertheless, they were incorporated into the model for completeness. However, in terms of sensitivity analysis, it is noticeable that all these variables share one common characteristic: they all have a reduced cost greater than or equal to their objective coefficient. This fact suggests that in reality, if their energy costs were zero or negative, it would be advantageous to exploit them. From a mathematical point of view, it seems logical. However, in the real world, this has no physical significance, as no processing can be carried out without incurring at least the minimum possible energy cost. Therefore, there is no practical value in considering these variables.

Moving on to the next four variables concerning type 2 WEEE, it is observed that all of them are zero, which means that WEEE type 2 are not utilized at all, according to the optimization model. Looking at the problem more closely we see that variables X_{21} and X_{23} have exactly the same objective coefficient (12), the same magnet recovery rate of 0.2% for Sr-Ferrite type magnet (Bonded & Sintered, respectively). It is also observed that they have the same reduced cost (4) which means that for their exploitation to make sense, their energy cost should be reduced by at least 4 units. Similarly, as long as their energy costs increase, obviously neither of these two specific streams will be used.

Similarities with the above-mentioned variables presents the variable X_{22}, which shares the same objective coefficient and recovery rate, but the reduced cost differs. This variable has a reduced cost of 2 indicating that in order to derive any benefit from its utilization, its objective coefficient would need to be reduced by at least 2 points. Corresponding to the previous ones, however much the energy cost (objective factor) increases, the production will remain zero.

Moving on to the next four variables concerning WEEE type 3, it is observed that all of them are zero, except X_{32}. Upon closer examination of the problem, we find similarities with the previous category of WEEE. We see that variables X_{31} and X_{33} have exactly the same objective coefficient (13), the same magnet recovery rate of 0.1% for Sr-Ferrite type magnet (Bonded & Sintered, respectively). It is also observed that they have the same reduced cost (11) which means that for their exploitation to make sense, their energy cost should be reduced by at least 11 units. Similarly, as long as their energy costs increase, obviously neither of these two specific streams will be used.

On the other hand, the variable X_{32} utilizes 70 kg of WEEE in order to produce bonded NdFeb magnet, precisely at the limit of constraint 9 concerning the capacity for WEEE type 3 without leaving any room to use WEEE of the same category to produce other magnets. With an objective factor of 13 and a recovery rate of 0.3%, the production of 21 kg of bonded NdFeb magnet is achieved at a total cost of 910 money units. Obviously, like the variable X_{13}, we can see that since has a non-zero value, it has no reduced cost. However, it is observed that the permissible increase is equal to 2 units. This implies that if the energy cost increases up to 2 units then the utilization of the 70 kg WEEE of this category will remain constant, but obviously with a higher total energy cost. However, for each unit above (e.g., 3 units, from 13 to 16), we cannot predict what will happen and whether the problem will present a feasible solution. On the other hand, at this point, it is clear that looking at the allowable reduction has infinite value which means that no matter how much energy costs decrease, the amount of production for that variable will remain the same.

The next category of WEEE type 4 has a particular interest because we see that 2 streams are utilized in order to produce magnets. At first, the variable X_{41} utilizes 45 kg of WEEE in order to produce bonded Sr-Ferrite magnet, leaving a quantity of 65 kg of WEEE to be utilized in order to reach the limit of constraint 10 concerning the capacity for WEEE type

4 to produce other magnets. With an objective factor of 8 and a recovery rate of 0.25%, the production of 11.3 kg of bonded Sr-Ferrite magnet is achieved at a total cost of 360 money units. Corresponding to the previous variables that were non-zero and used an amount of WEEE, this variable has no reduced cost. However, it is observed that the permissible increase is equal to 1.3 units. This implies that if the energy cost increases up to 1.3 units then the utilization of the 45 kg WEEE of this category will remain constant, but obviously with a higher total energy cost. But for each unit above (e.g. 2 units, from 8 to 10), we cannot predict what will happen and whether the problem will present a feasible solution. On the other hand, at this point it is easy to say that looking at the allowable reduction we see that it is almost zero. This in practice means that we are currently at a conceivable limit. If the price of energy costs is reduced by one unit, we are not sure what will happen to production. What is certain is that since it is a minimization problem and with this move, we reduce the energy cost and then the production of the specific magnet will increase (and consequently the usable amount of WEEE) resulting in the reduction of the amount used for variable X_{42} (to satisfy the constraint 10). However, this differentiation in the quantities of WEEE to be utilized cannot be known in advance.

In addition, the variable X_{42} utilizes the rest quantity of WEEE (65 kg) in order to produce bonded NdFeb magnet, reaching the limit of constraint 10. With an objective factor of 8 units and a recovery rate of 0.2%, the production of 13 kg of bonded Sr-Ferrite magnet is achieved at a total cost of 520 money units. Contrary to the previous variable, it is now observed that the permissible increase in the objective coefficient is almost zero, while the permissible decrease is equal to 1.3 units. The result is logical as only these two currents are utilized and have the same objective coefficient. Therefore, if the energy cost increases up to only 1 unit, then the utilization of the 65 kg WEEE of this category will not remain constant. This in practice means that we are currently at a conceivable limit. If the price of energy costs is increased by one unit, we are not sure what will happen to production and we cannot know what will happen and whether the problem will present a feasible solution. Probably, since that it is a minimization problem and with this move, we increase the energy cost and then the production of the specific magnet will reduce (and consequently the usable amount of WEEE) resulting in the increase of the amount used for variable X_{41} (to satisfy the constraint 10), but that's just a hypothesis. On the other hand, as it is already mentioned the allowable reduction is 1.3 units. So if the energy cost decreases up to only 1.3 units then the utilization of the 65 kg WEEE of this category will remain constant, but obviously with a lower total energy cost. But for each unit lower (e.g. 2 unit, from 8 to 6), we don't know in advance what will happen to the production but it is almost certain that the whole utilization of the stream X_{42} will be increased, resulting in the reduction of the amount used for variable X_{41}. However, this differentiation in the quantities of WEEE to be utilized cannot be known in advance.

Moving on, the variable X_{43} does not contributes to the production of Sintered Sr-Ferrite from WEEE type 4. With an objective coefficient of 8 units and a recovery rate of 0.1% it is observed that the existing quantity of these WEEE is not used at all. Obviously, it is not profitable the treatment of that stream in order to gain only 0.1% of magnet with this particular energy cost. As you can see from Figure 18 this variable has a reduced cost of 6 units, which means that in order to have any benefit from its utilization, its objective coefficient would have to be reduced by at least 6 units. The proposed reduction from the solution is huge and of course that is the reason that it is not preferred.

Moving on to the next four variables concerning WEEE type 5, it is observed that all of them have zero value, except X_{52}. We see that variables X_{51} and X_{53} have exactly the same objective coefficient (11), but not the same magnet recovery rate (0.3% for bonded Sr-Ferrite and 0.2% for sintered Sr-Ferrite). It is also observed that they have the different reduced costs. The variable X_{51} has a reduced cost of 3 units which means that for their treatment to make sense, their energy cost should be reduced by at least 3 units. Also, the variable X_{53} has a reduced cost of 7 units which means that for their treatment to make sense, their energy cost should be reduced by at least 7 units. On the contrary, as long as their energy costs increase, obviously neither of these two specific streams will be used.

On the other hand, the variable X_{52} utilizes 60 kg of WEEE in order to produce bonded NdFeb magnet, exactly at the limit of constraint 11 concerning the capacity for WEEE type 5 without leaving any room to use WEEE of the same category to produce other magnets. With an objective coefficient of 11 units and a recovery rate of 0.2%, the production of 18 kg of bonded NdFeb magnet is achieved at a total cost of 660 money units. Obviously, like the variable X_{32}, we can see that since has a non-zero value, it has no reduced cost. However, it is observed that the permissible increase is equal to 3 units (e.g. 3 units, from 11 to 14). This implies that if the energy cost increases up to 3 units, then the utilization of the 60 kg WEEE of this category will remain constant, but obviously with a higher total energy cost. But for each unit above (e.g. 4 unit, from 11 to 15), we cannot know what will happen and whether the problem will present a feasible solution. On the other hand, at this point it is easy to say that looking at the allowable reduction we see that it is infinite. This means that no matter how much energy costs decrease, the amount of production for that variable will be the same.

The last group of WEEE type 6 shows similarities with the aforementioned groups. Examining the X_{61} variable it is observed that it does not contribute to the production of bonded Sr-Ferrite magnet. With an objective coefficient equal to 10 units and a recovery rate of 0.1% it makes sense that the cost is high enough to extract such a small percentage of product. For this reason, a reduced cost equal to 6 is also observed, which implies, similar to the previous ones, that in order to make sense of the utilization of this stream, its energy cost should be reduced by at least 6 units.

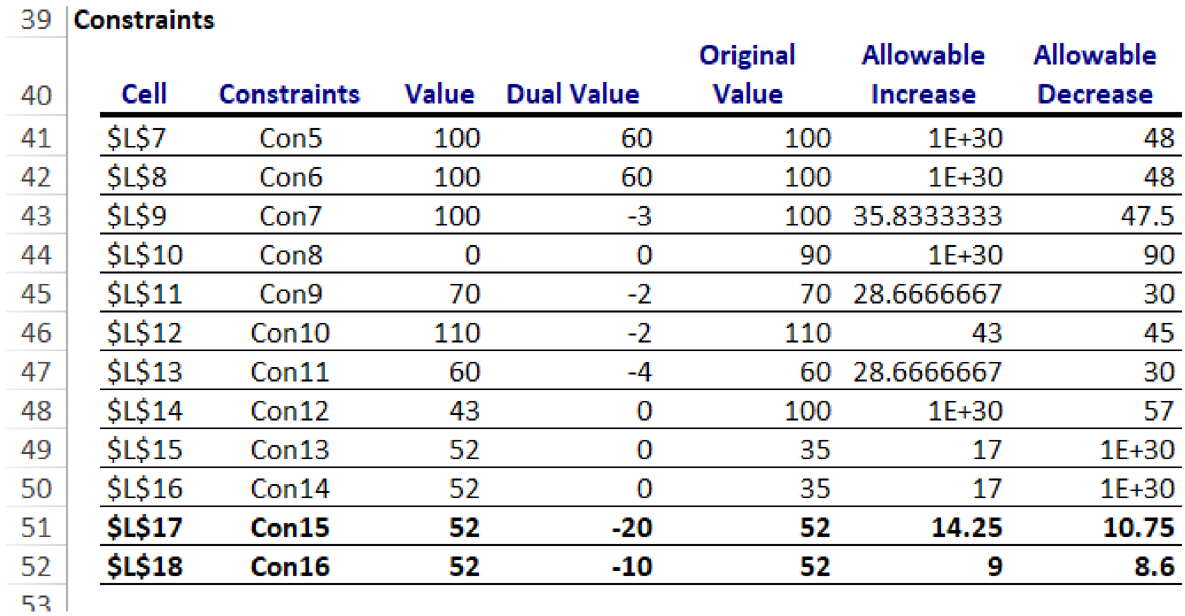
Similarities are demonstrated by the variable X_{62} which is also observed not to contribute to magnets production. With an objective coefficient of 10 units and a 0.2% recovery rate it makes sense that the cost is high enough to extract such a small percentage of product. For this reason, a very small reduced cost is observed, almost equal to zero, which implies that if the energy cost is reduced even for one unit (as you can see from the lower bound for this variable), then the production of the bonded NdFeb magnet will be economically advantageous. On the other hand, it is again obvious that no matter how much the energy cost increases, then the production will be zero.

On the contrary, it is observed that the variable X_{63} is utilized and contributes to the production of Sintered Sr-Ferrite magnet. With an objective coefficient equal to 10 and a magnet recovery rate equal to 0.25% it is observed that 43 kg are used. At this point it is observed that there remains a remaining 57 kg of WEEE to be used to fully cover the constraint 12 regarding the capacity of WEEE type 6. However, no other waste of this category is utilized leaving a slack to this constraint. Also, it is observed that 10.8 kg of sintered Sr-Ferrite magnet is produced at a total cost of 430 money units. Contrary to the previous variable (X_{62}), it is now observed that the permissible increase in the objective coefficient is almost zero, while the permissible decrease is equal to 1.3 units. Therefore, if the energy cost increases up to only 1 unit then the utilization of the 43 kg WEEE of this category will not remain constant. This in practice means that we are currently at a conceivable limit, like before. If the price of energy costs is increased by one unit, we are not sure what will happen to production and we cannot know what will happen and whether the problem will present a feasible solution. On the other hand, as it is already mentioned the allowable reduction is 1.3 units. So if the energy cost decreases up to only 1.3 units then the utilization of the 43 kg WEEE of this category will remain constant, but obviously with a lower total energy cost. But for each unit lower (e.g. 2 units, from 10 to 8), we don’t know in advance what will happen to the production but it is almost certain that the whole utilization of the stream X_{62} will be increased, without knowing in advance whether this increase will bring about a decrease in some other variable. However, this differentiation in the quantities of WEEE to be utilized cannot be known in advance.

Having finished with the analysis of the variables related to WEEE, it is now worth commenting on the two remaining variables related to the raw materials that IMA purchases directly from abroad to satisfy its demand. These specific variables do not have any limitation in terms of capacity or reserves, however what we aim for in the context of this project is to minimize their use, reducing the total energy costs and utilizing recyclable materials. The solution shows that to satisfy the demand of 100 kg, 48 kg of each type of magnet must be used. This results in a cost for each magnet raw material of 2.880 money units. As can be seen from the sensitivity analysis, these variables have no reduced cost.

However, for regarding the supply of magnet raw material, it is observed that no matter how much the objective factor increases, 48 kg of magnet will definitely be used to cover the demand, resulting in a higher total energy cost, of course. On the other hand, we see that the permissible reduction is 20 units. This implies that the utilization of 48 kg will remain constant up to a 20 unit decrease in the objective coefficient, while if it decreases further then we do not know what changes it will bring to the solution. The only thing that is certain is that since we are dealing with a minimization problem, the productivity of Sr-Ferrite magnets will be favored by directly buying raw material against some recycled quantity.

On the other hand, the variable z_2, which has the same objective coefficient, shows complete similarity in case of an increase in the objective coefficient. The supply of the 48 kg magnet will remain constant, with the result that we obviously have a higher total energy cost. On the other hand, the permissible reduction of the objective coefficient for this variable is 10 units. This implies that the utilization of 48 kg will remain constant up to a 10 unit decrease in the objective coefficient, while if it decreases further then we do not know what changes it will bring to the solution. The only thing that is certain is that since we are dealing with a minimization problem, the productivity of NdFeb magnets will be favored by directly buying raw material against some recycled quantity.



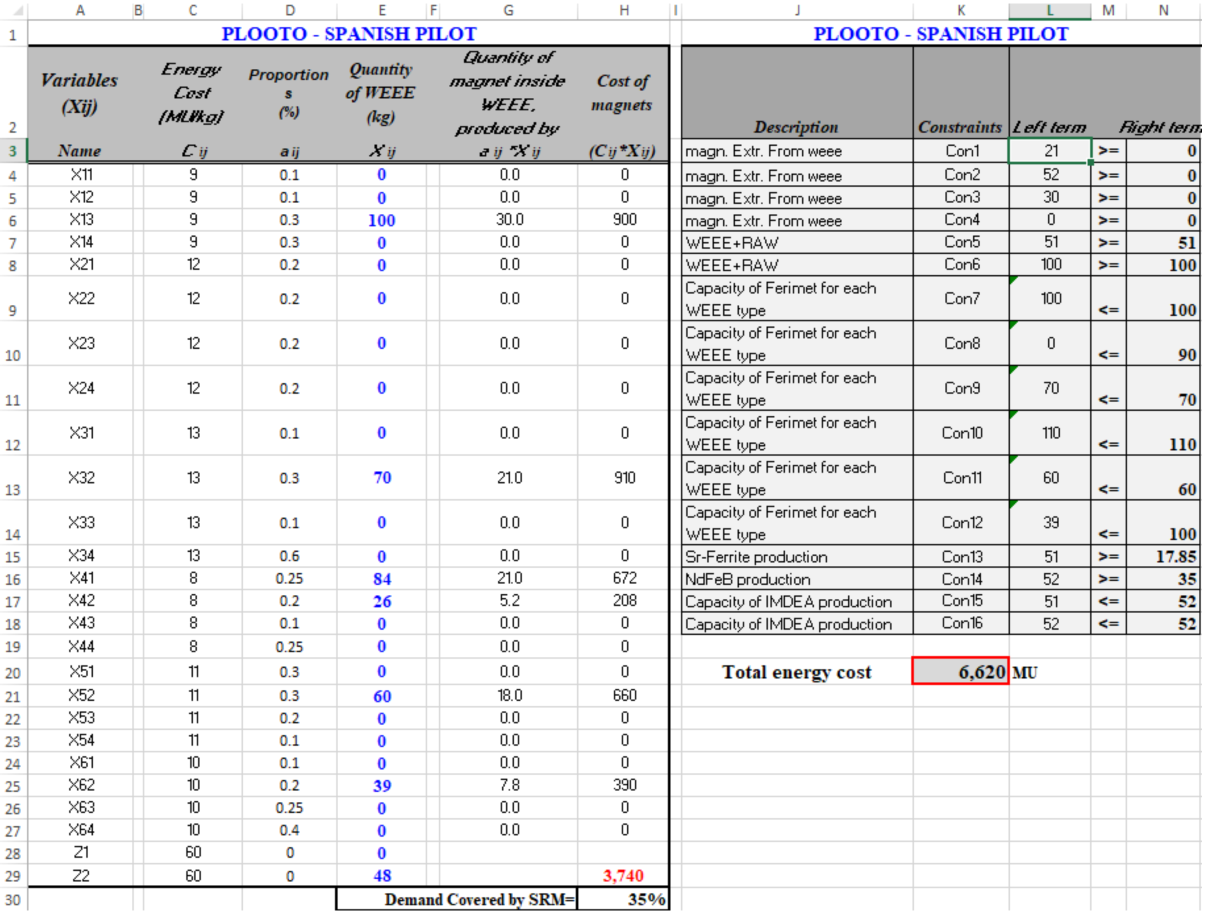
39 **Constraints**

	Cell	Constraints	Value	Dual Value	Original Value	Allowable Increase	Allowable Decrease
41	L7	Con5	100	60	100	1E+30	48
42	L8	Con6	100	60	100	1E+30	48
43	L9	Con7	100	-3	100	35.8333333	47.5
44	L10	Con8	0	0	90	1E+30	90
45	L11	Con9	70	-2	70	28.6666667	30
46	L12	Con10	110	-2	110	43	45
47	L13	Con11	60	-4	60	28.6666667	30
48	L14	Con12	43	0	100	1E+30	57
49	L15	Con13	52	0	35	17	1E+30
50	L16	Con14	52	0	35	17	1E+30
51	**L17**	**Con15**	**52**	**-20**	**52**	**14.25**	**10.75**
52	**L18**	**Con16**	**52**	**-10**	**52**	**9**	**8.6**

Figure 19*: Sensitivity analysis*

At this stage of the work, the project constraints will be commented on in detail, in conjunction with what was mentioned earlier about the decision variables. Unfortunately, the program we chose, in order to solve our problem, does not present the slacks/surplus for each constraint. However, in conjunction with what was discussed earlier this analysis yields useful results. As mentioned earlier, the Con1-Con4 constraints are auxiliary, and are useful to help us draw conclusions about the «behaviour» of the waste at a later stage of the research, not included in this thesis. When we talk about behaviour it is emphasized that we mean the type and quantity of magnets contained in the WEEE, in order to draw conclusions about the quantity of semi-finished products produced.

Advancing the analysis, we encounter a set of constraints that includes the two demand constraints to meet the quantity of Sr-Ferrite (Con5) and NdFeb (Con6) magnets. These are two binding constraints with no slack/surplus, and with a dual value equal to 60 MU. In practice, it is observed that the dual value is equal to the unit cost of purchasing each type of raw material. This implies that for each additional unit of production required by the demand, the total cost will be charged with 60 MU. In our problem, these constraints are inequalities ">=", thus expressing a requirement in the optimal solution to be satisfied at its lower bound, since we have a minimization problem to solve. However, the upper bound of the constraint extends to infinity, indicating that it can be fully satisfied with the amount of magnets that IMA will purchase in combination with the 52 kg per year from IMDEA. However, of interest is the lower bound of the constraint. It appears that the allowable reduction is 48 units (kg) which means that for every unit that demand is reduced the total energy cost will be reduced by 60 money units, up to the point where demand equals 52 kg of magnet. This is actually because for every one unit of demand that is reduced, one unit of raw material purchased by IMA is reduced at the same time. This is why the allowable reduction appears to be 48, which is also the kilos IMA will purchase to cover demand in conjunction with SRMs. However, if the demand is further reduced (e.g. the demand equals 51 units) as expected the dual value will decrease and the order of magnet production will change since it will now be profitable to produce such magnets from SRM only. The results are shown in the Figures 20 & 21 below.



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Variables (Xij)	Energy Cost (MU/kg)	Proportions (%)	Quantity of WEEE (kg)	Quantity of magnet inside WEEE, produced by	Cost of magnets
Name	Cij	aij	Xij	aij *Xij	(Cij*Xij)
X11	9	0.1	0	0.0	0
X12	9	0.1	0	0.0	0
X13	9	0.3	100	30.0	900
X14	9	0.3	0	0.0	0
X21	12	0.2	0	0.0	0
X22	12	0.2	0	0.0	0
X23	12	0.2	0	0.0	0
X24	12	0.2	0	0.0	0
X31	13	0.1	0	0.0	0
X32	13	0.3	70	21.0	910
X33	13	0.1	0	0.0	0
X34	13	0.6	0	0.0	0
X41	8	0.25	84	21.0	672
X42	8	0.2	26	5.2	208
X43	8	0.1	0	0.0	0
X44	8	0.25	0	0.0	0
X51	11	0.3	0	0.0	0
X52	11	0.3	60	18.0	660
X53	11	0.2	0	0.0	0
X54	11	0.1	0	0.0	0
X61	10	0.1	0	0.0	0
X62	10	0.2	39	7.8	390
X63	10	0.25	0	0.0	0
X64	10	0.4	0	0.0	0
Z1	60	0	0		
Z2	60	0	48		3,740
				Demand Covered by SRM=	35%

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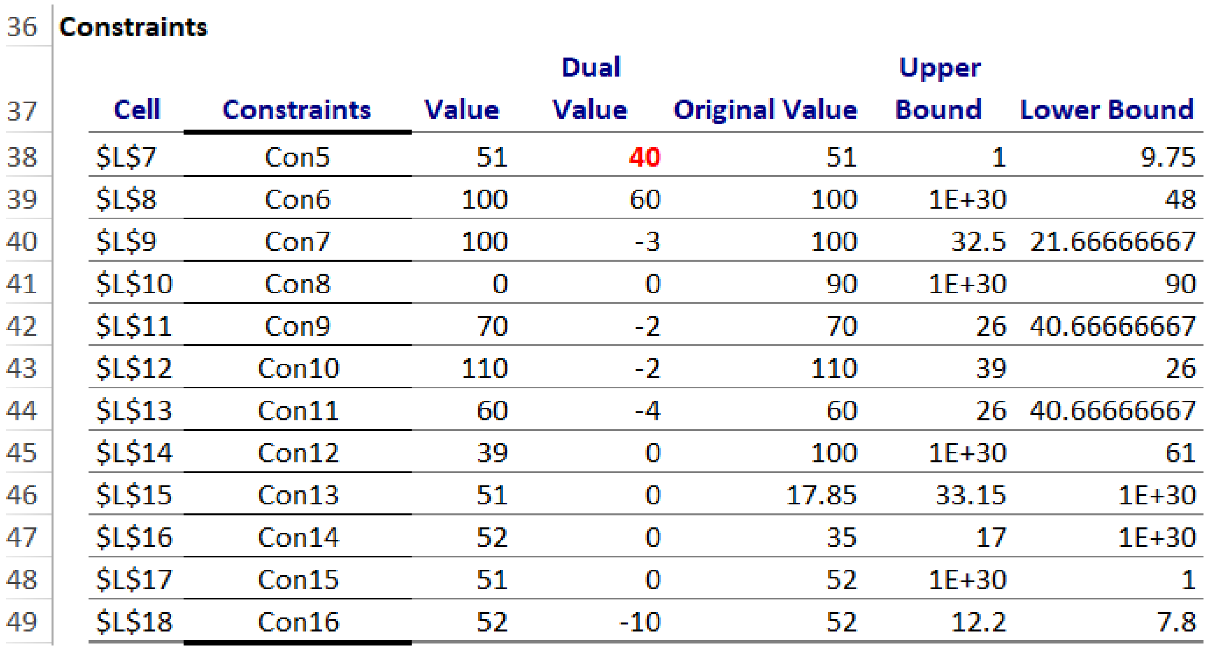
Description	Constraints	Left term		Right term
magn. Extr. From weee	Con1	21	>=	0
magn. Extr. From weee	Con2	52	>=	0
magn. Extr. From weee	Con3	30	>=	0
magn. Extr. From weee	Con4	0	>=	0
WEEE+RAW	Con5	51	>=	51
WEEE+RAW	Con6	100	>=	100
Capacity of Ferimet for each WEEE type	Con7	100	<=	100
Capacity of Ferimet for each WEEE type	Con8	0	<=	90
Capacity of Ferimet for each WEEE type	Con9	70	<=	70
Capacity of Ferimet for each WEEE type	Con10	110	<=	110
Capacity of Ferimet for each WEEE type	Con11	60	<=	60
Capacity of Ferimet for each WEEE type	Con12	39	<=	100
Sr-Ferrite production	Con13	51	>=	17.85
NdFeB production	Con14	52	>=	35
Capacity of IMDEA production	Con15	51	<=	52
Capacity of IMDEA production	Con16	52	<=	52

Total energy cost **6,620** **MU**

Figure 20: Solution Results, if we change the Demand for Sr-Ferrite



36	**Constraints**						
37	**Cell**	**Constraints**	**Value**	**Dual Value**	**Original Value**	**Upper Bound**	**Lower Bound**
38	L7	Con5	51	40	51	1	9.75
39	L8	Con6	100	60	100	1E+30	48
40	L9	Con7	100	-3	100	32.5	21.66666667
41	L10	Con8	0	0	90	1E+30	90
42	L11	Con9	70	-2	70	26	40.66666667
43	L12	Con10	110	-2	110	39	26
44	L13	Con11	60	-4	60	26	40.66666667
45	L14	Con12	39	0	100	1E+30	61
46	L15	Con13	51	0	17.85	33.15	1E+30
47	L16	Con14	52	0	35	17	1E+30
48	L17	Con15	51	0	52	1E+30	1
49	L18	Con16	52	-10	52	12.2	7.8

Figure 21: Constraints, after the change of the Demand for Sr-Ferrite

Our hypothesis is therefore proven that the net price is reduced if we exceed the lower bound for this constraint and at the same time a change of the used WEEE is observed in relation to the initial optimal solution of the problem. Now for each unit that is reduced in demand the total cost will be reduced by 40 money units until 9.75 kg of quantity demanded is reduced. For each additional unit that demand falls beyond the specified lower bound of the sensitivity interval, the value is expected to fall further until, in theory, demand becomes zero, which will have no physical existence thereafter.

Moving on, Constraint 6, which concerns the coverage of the requested demand in NdFeb magnet, has a similar philosophy to constraint 5. As can be seen, the demand is the same (100 kg of magnet) and the dual value is equal to 60 MU. Accordingly, the upper bound of the constraint extends to infinity which means that for each additional unit of quantity demanded, the total energy cost will increase by 60 MU. Correspondingly as before the lower bound in the sensitivity interval is equal to 52 (the allowable decrease is equal to 48 units). As expected for each unit that the demand decreases beyond the upper bound of the constraint the objective function will decrease, but it will not be the same as the previous constraint, as the amounts of magnet recovered from WEEE for each type of magnet are different. Accordingly, there will be a difference in the usable amount of WEEE for the production of this type of magnet (NdFeb) and raw material will no longer be purchased since it can now be fully covered by SRM.

Moving on to the next set of constraints on FERIMETs’ capacity, we encounter a set of 6 constraints (Con7-Con12). As depicted in Figure 21, all constraints are binding except constraints 8 and 12. It is observed that in constraint 8 we have a surplus of 90 units, which indicates that the specific amount of WEEE of this category has not been used at all. Constraint 12 has a surplus of 57 units, since only 43 kg were utilized from WEEE type 6. Constraint 8, as mentioned, is non-binding, which is a reasonable result considering the combination of the energy cost for extraction and the relatively low percentage content of magnets, leading the solver not to utilize them. This angle is practically interesting, suggesting that, due to the significant amount of WEEE, magnet extraction and recovery operations should be more developed. From a mathematical point of view, the sensitivity interval for this constraint extends from zero to infinity, meaning that increasing the capacity of the specific waste will have no effect on the solution's result. Conversely, the permitted reduction in capacity is 90 kg, indicating that if the capacity reaches zero, the solution's outcome— the amount used— will remain the same. Therefore, it is evident that the combination of energy costs with the quantitative content of magnets in this waste is not economically viable, regardless of the installation's capacity.

Concerning constraint 12, which pertains to the capacity in WEEE type 6, we observe that it is also a non-binding constraint, with a value of 43 kg within a sensitivity interval ranging from 57 to infinity. This practically means that the original value of the constraint, originally set at 100 kg, can shifts from 43 kg to infinity and the solution of the equation remains unchanged. Therefore, regardless of how much the capacity, of the specific facility, increases, the utilization amount of the specific waste will remain fixed at 43 kg. However, we cannot predict in advance what will happen with each additional unit of capacity reduction beyond the upper bound of the sensitivity interval. The most likely scenario is that this restriction will become binding, as the amount of WEEE used will then equal the amount specified by the constraint. At that point, a non-zero dual value will be observed, leading to a diversification of the utilization distribution of WEEE for magnet production to meet demand.

Moving forward, we evaluate the binding constraints starting from constraint 7, which has a dual value of 3 MU. Additionally, the permissible increase of the original value of the constraint is with 35.8 units while the permissible decrease is equal to 47.5 units. Accordingly, this implies that the sensitivity interval for the upper bound of the constraint is from 52.5 to 135.8 units. Since we have a minimization problem, as we move towards the upper bound of the constraint, the specific resource has a positive impact on the value of the objective function which means that for each additional unit of waste of the specific category that is used the total energy cost will be reduced by 3 MU. On the contrary, as we move towards the lower bound of the constraint, the energy cost for each unit of WEEE that is not utilized, will increase by 3 MU. If the original value of the constraint moves further from the lower bound of the sensitivity interval, then as expected the dual value of this constraint will increase which means that for each unit of WEEE type 2 that is not utilized energy costs will be more incurred. The opposite will happen if we move beyond the upper bound of the sensitivity interval, i.e. the dual value for the specific constraint is expected to decrease since we have a minimization problem.

Corresponding behavior, with different results, is expected from the rest of the constraints in the same category. For constraint 9 concerning the capacity in WEEE type 3, we observe that it is binding with a value equal to 70 kg. It is also noted that it has a permissible decrease of 30 kg and a permissible increase of 28.6 kg, that is, the sensitivity interval of the specific constraint extends to [40, 98.6] kg. Additionally, it is observed that the dual value of the constraint is equal to 2 MU. Therefore, as the original value of the constraint (capacity in WEEE type 3) approaches 98.6, for each unit that increases, the value of the objective function decreases by 2 MU. Beyond the upper bound of the sensitivity interval, the dual value is expected (as before) to decrease. In contrast to the above and similar to the previous constraint, for every unit that the original value of the constraint decreases and approaches the lower bound of the sensitivity interval, the value of the objective function is increased by 2 MU. Beyond the lower bound of the sensitivity interval, we don’t know what will happen to the dual value but probably will get increased. Therefore, for each unit less that is utilized by the specific WEEE category, the value of the objective function will be further increased. Another plausible assumption is that if the capacity, for the specific waste, is reduced, the demands of the demand should be covered by magnets coming from different WEEE. Therefore, the production of magnets from different WEEE will be take place.

For the constraint 10 concerning the capacity in WEEE type 4, we see that it is a binding constraint with a value equal to 110 kg. It is also observed that it has a permissible decrease of 45 kg and a permissible increase of 43 kg, meaning the sensitivity interval of the specific constraint extends to [65, 153] kg. Also, it is observed that the dual value of the constraint is equal to 2 MU. Therefore, for each unit that the original value of the constraint decreases and approaches the lower bound of the sensitivity interval, the objective function value is increased by 2 MU. Beyond the lower bound of the sensitivity interval, we do not know what will happen to the dual value but probably will get increased. Therefore, for each unit less that is utilized by the specific WEEE category, the value of the objective function will be further increased. Beyond the upper bound of the sensitivity interval, the dual value is expected (as before) to decrease. Like the previous constraint it is possible to say that if the capacity, for the specific waste, is reduced, the demands of the demand should be covered by magnets coming from different WEEE. Therefore, the production of magnets from different WEEE will be observed.

Moving on to the next constraint (con11), concerning the capacity in WEEE type 5, we see that it is binding with a value equal to 60 kg. It is also observed that it has a permissible decrease of 30 kg and a permissible increase of 28.6 kg, that is, the sensitivity interval of the specific constraint extends to [31.4, 90] kg. In addition, it is observed that the dual value of the restriction is equal to 4 MU. Therefore, as the original value of the constraint (capacity in WEEE type 5) approaches 90 kg, for each additional unit, the value of the objective function decreases by 4 MU. Beyond the upper bound of the sensitivity interval, the dual value is expected (as before) to decrease. In contrast to the above and similar to the previous constraint, for every unit that the original value of the constraint decreases and approaches the lower bound of the sensitivity interval, the value of the objective function is increased by 4 MU. Beyond the lower bound of the sensitivity interval, we do not know what will happen to the dual value but probably will get increased. Therefore, for each unit less that is utilized by the specific WEEE category, the value of the objective function will be further increased. Like the previous constraint it is possible to say that if the capacity, for the specific waste, is reduced, the demands of the demand should be covered by magnets coming from different WEEE. Therefore, the production of magnets from different WEEE will be observed.

Moving on to the next group of constraints concerning the finished product from IMDEA, we encounter 2 constraints (Con13-Con14). Both constraints are non-binding, have zero dual value, and they present a surplus of 17 kg. It can be seen that both have the same upper bound, equal to 35kg. This is because we assumed from the beginning that the IMDEA must cover at least 35% of the demand for the respective magnet with SRM. Also, the constraint gave a value equal to 52 kg for the variables m_i. The sensitivity interval is the same for both constraints, which is expected considering that we require the same amount of demand to be met for each magnet. The allowable decrease of the original value of the constraint is infinite while the allowable increase is equal to 17 kg (equal to surplus), so the sensitivity interval for these two constraints is (infinity, 52] kg. This constraint, however, has a peculiarity. The upper bound as we said varies according to the demand, since for the purposes of the project we require that at least 35% of the demand is covered by SRM. However, as mentioned at the beginning of this chapter, IMDEA has a capacity constraint. Because it is still a laboratory level plant, it cannot produce more than 1 kg for each magnet per week. For this reason, on an annual basis, it can produce only 52 kg each and as so, constraints 15 and 16 were introduced.

These constraints were introduced into the model because the production quantity from IMDEA must have a strict plateau of 52 kg, regardless of whether the demand is met at a rate of less than 35%. Therefore, in the event that the amount (35%) of the demand that must be covered by IMDEA exceeds 52 kg, then the problem will be infeasible. Therefore, for a larger quantity requested by IMA, IMDEA will not be able to deal with the demand and the project will not be feasible as its production ceiling is equal to 52 kg. However, from a mathematical point of view, no matter how much the requested production quantity of magnets is reduced, IMDEA will produce this 52 kg for each magnet, since it is a more economical option than buying the raw material.

Finally, the last group of constraints also concern the variable "m_i" which, as we mentioned, pertains to the production capacity from IMDEA. There are two constraints (Con15-Con16) and are binding. However, they present different dual values and different sensitivity intervals. Constraint 15, concerning the production of Sr-Ferrite magnet from SRM, has an allowable decrease value equal to 10.75 kg and an allowable increase equal to 14.25 kg. This results in a sensitivity interval that extends from 41.25 to 66.25 kg and presents a dual value equal to 20 MU. From the allowed reduction, we observe that for each unit less produced by the company the value of the objective function, i.e. the total energy cost, increases by 20 MU, until we reach the lower bound of the sensitivity interval. Beyond this boundary of the sensitivity interval, and for each unit less utilized, the dual value is expected to rise. However, this depends on the requested quantity by IMA. In this case, IMA may be covered with 35 kg by IMDEA's production. However, if the requested quantity (D_j) increases, then the dual values and the boundaries of the sensitivity interval will likely differ.

Constraint 16, concerning the production of NdFeb magnet from SRM, has an allowable decrease equal to 8.6 kg and an allowable increase equal to 9 kg. This results in a sensitivity interval that extends from 43.4 to 61 kg and presents a dual value equal to 10 MU. From the allowed reduction, we observe that for each unit less produced by the company the value of the objective function, i.e. the total energy cost increases by 10 MU, until we reach the upper bound of the sensitivity interval. Beyond this boundary of the sensitivity interval, and for each unit less utilized, the dual value is expected to rise However, as before, this depends on the requested quantity by IMA.

Obviously, there is no reason to comment on either of the above two constraints, what would happen if we moved towards the upper bound of the sensitivity interval, since it is clear that under no circumstances can the production capacity of IMDEA exceed 52 kg for any of the two types of magnets.

5 Conclusions – Limitations – Future Research

The recovery of WEEE plays a key role in environmental sustainability because it minimizes the negative effects of hazardous materials and contributes to the conservation of limited resources around the world. In order to play their role in environmental sustainability, WEEE recycling facilities must be profitable. Therefore, it is important to create efficient and profitable operational level decisions for these facilities. This study presents a linear programming (LP) model to calculate the offered amount of magnets from WEEE, combined with the minimization of the total energy cost. The model applies to recycling facilities that collect WEEE in combination with waste reprocessing facilities to produce products, namely permanent magnets.

The main object of the present thesis is the creation and evaluation of a linear optimization model that selects the quantities of each type of WEEE that will be used for disassembly and the production of permanent magnets from SRM. On this direction, the model was examined using artificial data, because there was a lack of data collection from the companies.

After the model was solved using Excel, the optimal solution that emerged was that the total energy cost based on the data amounted to 9,540 MU. It was observed that a whole category of waste (WEEE type 2) is not proposed to be used at all in the production process as the combination of energy cost - percentage of magnetic content had no economic benefit in relation to the corresponding variables of the rest of the waste. At this point, perhaps we could emphasize the fact that the largest volume of magnets was provided by WEEE type 1 and type 3, apparently due to the good correlation between magnet quantity and energy cost they displayed. It is worth mentioning that there is great uncertainty regarding the percentages of magnet in WEEE as they were derived from artificial data. On this point it’s worth saying that the biggest changes that this pilot seeks are related to Ferimet’s operations. With the support of the tech partner, the company expects to design an automated and robotic process to dismantle magnets specifically from motors and engines. This is an event that will upgrade the efficiency and effectiveness of the company, reducing production times (extraction of magnets from WEEE), reducing the margins of error and mistakes that exist in any production process where the human factor is involved. It will also lead to an increase in productivity as the automated plant will be able to operate seamlessly and without deviations on a full-time basis.

Moving on, it is evident that the entire amount of NdFeb pellets produced by IMDEA comes exclusively from Bonded NdFeb, while the Sr-Ferrite pellets that comes from sintered

Sr-Ferrite is almost three times that of bonded Sr-Ferrite. It is worth mentioning that FERIMET's capacity would be able to cover the proportionate amount of WEEE in order to cover the total demand of the magnets. However, this too is limited by the low capacity of IMDEA laboratory. From the results it is observed that the capacity of IMDEA has reached its limits, which is a worrying fact.

Several limitations exist regarding the recovery of Waste Electrical and Electronic Equipment. The volatility in magnet content within Waste Electrical and Electronic Equipment (WEEE) poses a significant challenge in the recycling and management of electronic waste. The fluctuations in electronics' design and production further complicate matters, making it challenging for recycling facilities to predict and efficiently reclaim these precious materials. This is an important limitation also for the LP model developed, as we cannot know in advance the exact amount of magnetic material for each WEEE. Additionally, an important constraint concerns IMDEAs' production capacity. On a theoretical level and provided that the latter can satisfy a larger proportion of the quantity demanded, the present model is fully linear and if the use of SRMs is more economical than raw materials, then they will be fully used for the production of magnets. The model is therefore limited and does not take into account any changes that may occur in energy costs if the plants' capacity is able to meet a greater amount of demand (e.g. by changing the machines in production process and reducing energy costs, or by a state-economic reward if a larger proportion of demand can be met by SRMs). These examples are essential and particularly important, since if the energy costs of producing magnets from SRMs and raw materials are almost equal, then such rewards and/or energy cost reductions due to an increase in the quantity produced could play a catalytic role in tipping the scales in favour of SRMs.

To address the intricate challenge of managing the volatility in magnet content within WEEE while considering stochasticity, a Mixed Integer Linear Programming (MILP) model could optimize resource allocation and decision-making processes, accommodating the uncertainty surrounding magnet composition and quantity in electronic waste. By incorporating stochastic elements like probability distributions for magnet volatility and market demand the MILP model can devise robust strategies to navigate uncertainties and improve the overall efficiency. In contrast, to address the next constraint, in future steps we need to consider how we could incorporate piecewise functions to account for behavioral changes (e.g., economic rewards) depending on the amount of SRM used for production of permanent magnets. As it is expected that the European Union in the coming years will implement reward policies for companies that apply circular economy practices (e.g. use of alternative raw materials for the production of products), the use of segmental functions that will take into account these rewards and changes in the production process, are considered necessary to be integrated in the corresponding model created in this thesis as it will improve the possibilities of predicting optimal strategies for increasing the total systems' efficiency.

Generally, investments in infrastructure for WEEE recovery is essential for scaling up recycling operations. This includes expanding collection networks, upgrading recycling facilities, and improving logistics for transporting electronic waste. Infrastructure development should also prioritize the establishment of environmentally responsible end-of-life treatment facilities for hazardous components. Governments play a crucial role in shaping the future of WEEE recovery through policy and regulation. Future steps should involve the development and implementation of comprehensive regulatory frameworks that promote sustainable WEEE management practices. This includes policies such as extended producer responsibility (EPR), mandatory recycling targets, and eco-design requirements for electronic products. Additionally, given the global nature of the electronics industry and the transboundary movement of electronic waste, international collaboration is critical for effective WEEE recovery. By focusing on these key areas and implementing coordinated efforts across stakeholders, the future of WEEE recovery can be characterized by increased efficiency, sustainability, and circularity in the management of electronic waste.

In summary, the recovery of useful materials from waste electrical and electronic equipment is far from their full contribution to the creation of circular economy units and the production of products from secondary raw materials on a large scale. It is necessary to continue the efforts and researches to be able to reduce the amounts of WEEE that end up in landfills or are left unchecked in the environment, with the aim of integrating them into the core of industrial activity and creating environmentally friendly processes and products.

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