UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Mapping, Modeling and Improving the WEEE Treatment and Recovery: A Portuguese Case Study

Eduardo Luís Mesquita Santos

Supervisor: Doctor Paulo Manuel Cadete Ferrão
Co-Supervisor: Doctor Fernanda Maria Ramos da Cruz Margarido

Thesis approved in public session to obtain the PhD Degree in
Leaders for Technical Industries

Jury final classification: Pass with Merit

Jury
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Doctor António José Boavida Correia Diogo
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2013

Para a minha família, em especial para
o meu pai, para a minha mãe e para a minha irmã.

Mapeamento, Modelação e Melhoria do Tratamento e Valorização de REEE: O Caso de Estudo Português

Eduardo Luís Mesquita Santos

Doutoramento em Líderes para Indústrias Tecnológicas

Orientador: Paulo Manuel Cadete Ferrão

Co-Orientador: Fernanda Maria Ramos da Cruz Margarido

Resumo

A falta de conhecimento sobre tecnologias usadas para processar resíduos de equipamentos elétricos e eletrónicos (REEE) constitui a principal barreira para o seu eficiente e eficaz tratamento e valorização. Na Europa e em outros países do mundo, os produtores de equipamentos elétricos e eletrónicos constituíram, e financiam, organizações de responsabilidade do produtor (PRO) legalmente responsáveis pela recolha, tratamento e valorização de REEE. A investigação realizada teve como objetivo fundamental desenvolver um modelo global da infraestrutura de processamento de REEE com base na caracterização das operações segundo aspetos técnicos, económicos e ambientais para o que foi realizado um extenso trabalho de campo. O modelo foi validado com dados obtidos para as tecnologias de processamento em fim de vida existentes na infraestrutura Portuguesa e a jusante desta.

O modelo foi aplicado ao caso de estudo da infraestrutura Portuguesa com o objetivo de aumentar o seu desempenho técnico, económico e ambiental, tendo os resultados obtidos comprovado um aumento significativo de todas as vertentes estudadas no tratamento e valorização de REEE.

O modelo global técnico, económico e ambiental resultante do trabalho de investigação pode ser utilizado pelas PRO para avaliar e aumentar o desempenho do tratamento e valorização de REEE.

Palavras-chave: Modelo técnico, económico e ambiental; Uso eficiente de tecnologias de processamento em fim de vida; Desempenho do tratamento e valorização de resíduos de equipamentos elétricos e eletrónicos (REEE); Infraestrutura Portuguesa.

Mapping, Modeling and Improving the WEEE Treatment and Recovery: A Portuguese Case Study

Abstract

The lack of knowledge on the technologies used to process waste electrical and electronic equipment (WEEE) is the main barrier for their efficient and effective treatment and recovery. In European and other countries worldwide, the producers of electrical and electronic products constituted and finance producer responsibility organizations (PRO) legally responsible to collect, treat and recover the WEEE. The research work performed had the fundamental objective of developing a global model of the infrastructure for processing of WEEE based on the characterization of operations according with the technical, economical and environmental aspects, for which an extensive field work was executed. The model was validated with data obtained on the end of life processing technologies existing in the Portuguese infrastructure and downstream of this.

The model was applied to a case study of the Portuguese infrastructure with the objective of improving its technical, economical and environmental performance, having the results obtained proved a significant increase of all the aspects studied in the treatment and recovery of the WEEE.

The technical, economical and environmental global model resulting from the research work can be used by the PRO's to assess and increase the performance of the treatment and recovery of WEEE.

Key words: Technical, economical and environmental model; Efficient use of end-of-life processing technologies; Performance of treatment and recovery of waste electrical and electronic equipment (WEEE); Portuguese infrastructure.

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Acronyms

AMB3E	Associação Portuguesa de Gestão de Resíduos
ANREEE	Associação Nacional para o Registo de Equipamentos Elétricos e Eletrónicos (Producer Registry Entity, in english)
APA	Agência Portuguesa do Ambiente (Portuguese Environment Agency, in english)
CFC	Chlorofluorocarbons
CRT	Cathode Ray Tube
EEE	Electrical and Electronic Equipment
ELV	End-of-life Vehicles
EoL	End-of-life
EPR	Extended Producer Responsibility
ErP Directive	Directive 2009/125/EC
ERP Portugal	European Recycling Platform Portugal, Associação Gestora de REEE
EU	European Union
EuP Directive	Directive 2005/32/EC
EWL	European Waste List
GWP	Global Warming Potential
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCIA	Life Cycle Impact Assessment
License AMB3E	Joint dispatch n.º354/2006, of 27th of April, of the Ministry of Environment and the Ministry of Economy
License ERP Portugal	Joint dispatch n.º353/2006, of 27th of April, of the Ministry of Environment and the Ministry of Economy
PBB	Polybrominated Biphenyls
PBDE	Polybrominated Diphenyl Ethers
PCB	Polychlorinated Biphenyls
PCB/PCT	Polychlorinated Biphenyls and Polychlorinated Terphenyls
PRO	Producer Responsibility Organization
RoHS Directive	Directive 2002/95/EC
SIRER	Sistema Integrado de Registo Eletrónico de Resíduos (Integrated Waste Data Registry Sistem, in english)
WEEE	Waste Electrical and Electronic Equipment
WEEE Directive	Directive 2002/96/EC
WEEE Recast	Directive 2012/19/EU

Glossary

Terms	Definitions
Extended Producer Responsibility	Responsibility of producers for the end-of-life management of their products.
End-of-life processing chain	Series of subsequent processors and processing operations that transform material inputs (e.g. waste electrical and electronic equipment) until they are recovered (by reuse, recycling or energy recovery) or eliminated (by incineration without energy recovery or disposal in landfill).
Processing techniques	Set of operations used to transform a material input (e.g. waste electrical and electronic equipment) into one or more material outputs (e.g. fractions such as parts or materials, like cables, copper, plastic, etc.).
Recovery techniques (including recycling and energy recovery)	Set of processes used to transform a secondary material input (e.g. fractions such as secondary materials, like steel, copper, plastic, etc.) into the production of a new product (by recycling) or to incinerate it and produce electricity or heat (by energy recovery).
Processor/Operator	Organization that processes waste or material fractions by applying processing technologies.
Producer Responsibility Organization	Organization where producers of electrical and electronic equipment are represented, which is licensed by the national government to implement and develop a take back scheme.
Reuse	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived.
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations (Directive 2008/98/EC). Includes primary and secondary recycling and may include tertiary recycling.
Recovery	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy (Directive 2008/98/EC). Includes primary, secondary, tertiary and quaternary recycling.
Disposal or Elimination	Any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy.
Treatment	End-of-life processing operations, including preparation prior to recovery or disposal.
Final acceptor	Organization that with its activity does reuse, recycling, recovery or elimination of waste.

1 Introduction

The estimates of the United Nations University indicate that between 8.3 and 9.1 million tons of waste electrical and electronic equipment (WEEE or e-waste) were produced across the 27 members of the European Union (EU) in 2005. A number of forecasting assumptions were applied which predict that the total amount of WEEE will grow between 2.5% and 2.7% annually, reaching approximately 12.3 million tons by 2020 (United Nations University, 2007). Despite the recent emerging of the economic crisis, with steady decline in sales of electrical and electronic equipment (EEE) in Europe, the number of appliances entering the global market every year is increasing, in both developed and developing countries (Schluep et al., 2009) and so it is expected that the total amount of discarded electrical and electronic equipment will continue to be very significant.

Considering the material composition of WEEE, it can be regarded as a resource of valuable metals such as copper, aluminium and gold, as well as resource of plastics (Ongondo et al., 2011). Recently, WEEE has also become an important source for a set of high value chemical elements, specifically the lanthanides, scandium and yttrium, also known as rare earth metals. These materials are part of the list of critical raw materials at EU level considering the risk of supply and their economic importance (European Commission, 2010). When such resources are not recovered, raw materials have to be extracted and processed in order to make new products, resulting in significant loss of resources and environmental damage from mining, manufacturing, transport and energy use (Cui and Forssberg, 2003; Bains et al., 2006 and Bohr, 2007). WEEE also holds various hazardous substances and/or components in their composition that may present a threat to the environment and to humans in case they are not treated and recovered (United Nations University, 2007).

The large quantities of the WEEE and the wide variety of materials it contains (many potentially harmful to both humans and the environment) have focused attention on how the WEEE is generated and ways in which it can be prevented (Ongondo et al., 2011). The potential adverse health and environmental consequences of incorrect handling and treatment of the WEEE (e.g. in China, India, etc.) has further heightened concerns in relation to its management (Fishbein, 2002; Puckett et al., 2003; Natural Edge Project, 2006). In this context, Europe has been a pioneer with the development of a legal framework to address the environmental issues of WEEE, namely waste management and prevention, but also the improvement of new electrical and electronic products through ecodesign.

The European Directive 2002/96/EC (WEEE Directive) was developed and entered into force in 2002. It was later transposed to the Portuguese national law by Decree-law n.º 230/2004. It required manufacturers and importers in the EU Member States to take back their products from end users and ensure that they were disposed of using environmentally sound methods (Widmer et al., 2005). The WEEE Directive introduced the Extended Producer Responsibility (EPR) principle to the WEEE and allowed producers to fulfil their responsibility by implementing individual or collective take back schemes (European Commission, 2003b). Throughout European Member State countries producers developed collective take back schemes managed by non-profit organizations, producer associations or companies here designated as Producer

Responsibility Organizations (PRO). In Portugal, producers of EEE organized in two PRO's: AMB3E, Associação Portuguesa de Gestão de Resíduos (AMB3E) and European Recycling Platform Portugal, Associação Gestora de REEE (ERP Portugal). Each PRO was licensed by the competent Portuguese government authorities, the *Agência Portuguesa do Ambiente* (APA, the Portuguese Environment Agency) of the Ministry of Environment and by the Ministry of Economy.

The producers of EEE, through the respective PRO, are legally required to collect a minimum amount of WEEE each year, ensure the proper treatment and fulfil minimum percentages of reuse/recycling and recovery (European Commission, 2003b). In order to do so, PRO's are legally mandated to develop and implement WEEE take back schemes, providing the infrastructure and financing of the WEEE management operations, including the collection, sorting, transportation, treatment, recovery and/or elimination. In order to do so, the PRO's sign contracts with the waste management operators, from the public and private sectors that provide the facilities, the personnel and the technologies to manage the WEEE.

Regarding the WEEE treatment and recovery, the relative underdevelopment of the sector in Europe by the time the WEEE Directive was developed posed significant challenges in terms of the capability of the installed technologies to process the amounts of WEEE being collected, and also to achieve the performance levels required to fulfil the legal targets of reuse/recycling and recovery. By providing a stable feed of input material as well as the financial support to the end-of-life processing operators over the years, the PRO's in Europe have progressively supported the development of the WEEE treatment and recovery sector. Despite the systemic and technological developments, global problems in recycling waste electrical and electronic equipment still remain in the lack of technologies and the misuse of those currently available to handle the complex products that are discarded, because the knowledge of how to do so is owned by the recycler (Kuo, 2010). The unavailability of knowledge on the end-of-life technologies for stakeholders, such as the PRO's, the policy makers and the producers of EEE, is a barrier for the efficient and effective management of the WEEE and as a consequence optimizing product recovery is often hindered (Zuidwijk and Krikke, 2008).

In this context, the availability of information is critical for PRO's to develop the efficient use of the technologies involved in the end-of-life management of discarded electrical and electronic equipment, to ensure the legal compliance and improve the technical, economic and environmental performance of the WEEE treatment and recovery. The availability of knowledge on the current end-of-life technologies is also important to assess the need to develop new technologies for end-of-life processing and recovery of the WEEE as well as to assist the design of new products to improve the end-of-life performance (Kuo, 2010).

The research work focused on developing a global model of the end-of-life processing infrastructure for WEEE based on the characterization of processes and their technical, economic and environmental aspects, which was developed through an extensive field work. The model was calibrated with the technologies installed in the Portuguese infrastructure for end-of-life processing of WEEE. A specific case study was developed to demonstrate the benefits of the model to improve the performance of the Portuguese infrastructure.

1.1 WEEE management in an EPR context

1.1.1 European legal framework

In the last decade the European Union has pushed forward several activities for environmental legislation, affecting especially the electronics and electrical industry. Concerning the end-of-life management of waste electrical and electronic equipment, the EU has developed and promulgated Directive 2002/96/EC of 27 January 2003 (WEEE Directive) later amended by Directive 2003/108/EC of 8 December 2003. Just recently, in July 2012, a recast version of the WEEE Directive entered in to force, Directive 2012/19/EU (WEEE Recast) and EU member countries have 18 months to transpose it to the respective national laws.

The main principles embarking the spirit of the WEEE Recast are the prevention of waste production and subsequently its recovery and the producer's responsibility over their products, especially concerning the end-of-life stage. The Extended Producer Responsibility principle has become predominant in respect to the management of waste generated from discarded products, including electrical and electronic equipment. In order to give maximum effect to the concept of producer responsibility, each producer should be responsible for financing the management of the waste from his own products. Additionally, producers have to support the management of historical waste (resulting from products put on the market before 13th of August 2005, according with the WEEE Directive) in the proportion of the respective market share. The Directive allows producers to fulfil the obligations either by developing an individual take back system or by joining a collective one.

The WEEE Directive established minimum targets for separative collection, recovery and recycling of WEEE, which have been revised and increased in the WEEE Recast. Accordingly, EU Member States now have to achieve a minimum rate of separative collection of WEEE as follows:

- Until 31st of December 2015: 4 kilogram per inhabitant per year of WEEE from households;
- From 1st of January 2016 until 31st of December 2018: 45% of the average annual weight of EEE placed on the market during the three preceding years, of WEEE from households and professional activities;
- From 1st of January 2019: 85% of the amount of WEEE generated annually, or alternatively, 65% of the average annual weight of EEE placed on the market during the three preceding years, of WEEE from households and professional activities.

The WEEE has to undergo proper treatment, which shall, as a minimum, include the removal of all fluids and the selective treatment for materials and components. The following substances, mixtures and components have to be removed from any separately collected WEEE and shall be disposed or recovered appropriately (European Commission, 2012a):

- polychlorinated biphenyls (PCB) containing capacitors in accordance with Council Directive 96/59/EC of 16 September 1996 on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT),
- mercury containing components, such as switches or backlighting lamps,
- batteries,

- printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimetres,
- toner cartridges, liquid and paste, as well as colour toner,
- plastic containing brominated flame retardants,
- asbestos waste and components which contain asbestos,
- cathode ray tubes,
- chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), hydrocarbons (HC),
- gas discharge lamps,
- liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimetres and all those back-lighted with gas discharge lamps,
- external electric cables,
- components containing refractory ceramic fibres as described in Commission Directive 97/69/EC of 5 December 1997 adapting to technical progress for the 23rd time Council Directive 67/548/EEC on the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances,
- components containing radioactive substances with the exception of components that are below the exemption thresholds set in Article 3 of and Annex I to Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation,
- electrolyte capacitors containing substances of concern (height >25 mm, diameter >25 mm or proportionately similar volume).

Also, the following components of the WEEE that is separately collected have to be treated as indicated:

- Cathode ray tubes: the fluorescent coating has to be removed;
- Equipment containing gases that are ozone depleting or have a global warming potential (GWP) above 15, such as those contained in foams and refrigeration circuits: the gases must be properly extracted and properly treated. Ozone-depleting gases must be treated in accordance with Regulation (EC) N.º 1005/2009;
- Gas discharge lamps: the mercury shall be removed.

The WEEE Directive defined ten legal categories of waste electrical and electronic equipment (see Annex I). Regarding WEEE separately collected and sent for treatment, the WEEE Directive established minimum rates for reuse and recycling as well as for recovery individually for each of the ten legal categories, with the exception of legal category 8 Medical devices, that had no target assigned. The WEEE Recast increased those targets by 5%, in general, and also defined for the first time the targets concerning WEEE of legal category 8. Table 1.1 presents the new minimum reuse/recycling and recovery targets of the WEEE according with the WEEE Recast.

Table 1.1 – Minimum Reuse/Recycling and Recovery targets until August 14, 2018 (European Commission, 2012a)

Categories	Until August 14, 2015		From August 15, 2016 until August 14, 2018	
	Reuse/Recycling targets	Recovery targets	Reuse/Recycling targets	Recovery targets
1. Large household appliances	≥ 75%	≥ 80%	≥ 80%	≥ 85%
2. Small household appliances	≥ 50%	≥ 70%	≥ 55%	≥ 75%
3. IT and telecommunications equipment	≥ 65%	≥ 75%	≥ 70%	≥ 80%
4. Consumer equipment and photovoltaic panels	≥ 65%	≥ 75%	≥ 70%	≥ 80%
5. Lighting equipment	≥ 50%	≥ 70%	≥ 55%	≥ 75%
5.1 Gas discharge lamps	≥ 80%	–	≥ 85%	–
6. Electrical and electronic tools	≥ 50%	≥ 70%	≥ 55%	≥ 75%
7. Toys, leisure and sports equipment	≥ 50%	≥ 70%	≥ 55%	≥ 75%
8. Medical devices	≥ 50%	≥ 70%	≥ 55%	≥ 75%
9. Monitoring and control instruments	≥ 50%	≥ 70%	≥ 55%	≥ 75%
10. Automatic dispensers	≥ 75%	≥ 80%	≥ 80%	≥ 85%

From August 15, 2018 onwards, the WEEE Recast sets minimum reuse/recycling and recovery targets according with new categories of electrical and electronic equipment. Instead of the ten legal categories, it defines a new set of six categories. Table 1.2 presents the referred reuse/recycling and recovery targets.

Table 1.2 – Minimum Reuse/Recycling and Recovery targets from August 15, 2018 (European Commission, 2012a)

Categories	From August 15, 2018	
	Reuse/Recycling targets	Recovery targets
1. Temperature exchange equipment	≥ 80%	≥ 85%
2. Screens, monitors, and equipment containing screens with a surface >100 cm^2	≥ 70%	≥ 80%
3. Lamps	≥ 80%	–
4. Large equipment (any external dimension >50 cm)	≥ 80%	≥ 85%
5. Small equipment (no external dimension >50 cm)	≥ 55%	≥ 75%
6. Small IT and telecommunication equipment (no external dimension >50 cm)	≥ 55%	≥ 75%

This new set of categories defined in the WEEE Recast can be interpreted as an effort to minimize the gap between the definition of the legal targets and its applicability on the field, as it is explained in the following paragraphs.

For the purpose of assessing the compliance with the legal targets, producers or third parties acting on their behalf have to keep records of the weight of the WEEE, its components, materials or substances when leaving (output) the collection facility, entering (input) and leaving (output) the treatment facilities and when entering (input) the recovery or recycling/preparing for reuse facility. They also have to ensure that records are kept of the weight of products and materials when leaving (output) the recovery or recycling/preparing for reuse facility.

Despite these requirements, there is still a gap between the definition of the legal targets and its applicability on the field. Considering the current end-of-life technologies, in order for the operations of treatment and recovery to be effective and efficient, the WEEE is sorted in five treatment categories that are distinct from the ten legal categories. This operational practice is done based on the similarity of characteristics of the different equipment that make up the WEEE to match the specifications of the subsequent treatment and processing technologies. The 5 main WEEE treatment categories are:

- Large household appliances (treatment category A);
- Cooling and freezing appliances (treatment category B);
- Small domestic appliances (treatment category C);
- Gas discharge lamps (treatment category D);
- Cathode ray tube (CRT) televisions and monitors (treatment category E).

Since the WEEE is processed in five distinct treatment categories, and not under the ten legal categories, the assessment of the percentages of reuse/recycling and recovery by treatment category is most accurate if it is based on data from the operational practice. The mass balance accounting for the WEEE of each of the ten legal categories would be physically possible, by doing selection of specific samples and testing them in the treatment facilities, but would become too expensive and time consuming, as it would require significant labour to select the samples, increasing the human resources and time spent to characterize the processing of the WEEE according with the legal categories. In practice this is not feasible and the rates of reuse/recycling and recovery are effectively measured based on the five treatment categories. The results can be converted from the five treatment categories in to the ten legal categories by using statistical data on the composition of the WEEE, for example, by sampling and classification procedures (Luízio, 2009).

In this context, a methodology is necessary to calculate reuse/recycling and recovery rates. The WEEE Forum, an association of 40 collective WEEE take back systems working at national level in 22 European countries, including AMB3E from Portugal, has proposed a methodology that converts the targets defined in the WEEE Directive from the legal categories in to the treatment targets. The development and application of this methodology allows the assessment of compliance of the operational results on reuse/recycling and recovery with the legal targets (Luízio, 2009).

The methodology uses data from sampling of collected WEEE that is classified to determine the average representativeness, in percentage by weight, of the different legal categories in each of the five treatment categories. The representativeness factor of each legal category is multiplied

by the respective legal target on reuse/recycling and recovery. The result is added to the results of all legal categories that constitute the treatment category and provide the converted legal target. Table 1.3 shows the conversion of the reuse/recycling and recovery targets from legal categories to treatment categories.

Given the legal categories that compose each treatment category of WEEE and the legal targets in force presently, only for the WEEE of treatment category C (Small domestic appliances) the result depends on the representativeness data from sampling and classification procedures. In Portugal, AMB3E has been using this methodology since its development in 2006, for which it had to develop and implement sampling and classification procedures to characterize the WEEE that it collects.

Table 1.3 – Conversion of legal targets for reuse/recycling and recovery from legal categories to treatment categories

<table>
<tr><th rowspan="2">Treatment categories</th><th rowspan="2">Legal categories</th><th colspan="2">Legal categories</th><th colspan="2">Treatment categories</th></tr>
<tr><th>Reuse/Recycling target (%)</th><th>Recovery target (%)</th><th>Reuse/Recycling target (%)</th><th>Recovery target (%)</th></tr>
<tr><td>Large household appliances (A)</td><td>1. Large household appliances</td><td>75%</td><td>80%</td><td>75%</td><td>80%</td></tr>
<tr><td rowspan="3">Cooling and freezing appliances (B)</td><td>1. Large household appliances</td><td>75%</td><td>80%</td><td rowspan="3">75%</td><td rowspan="3">80%</td></tr>
<tr><td>8. Medical devices</td><td>-</td><td>-</td></tr>
<tr><td>10. Automatic dispensers</td><td>75%</td><td>80%</td></tr>
<tr><td rowspan="9">Small domestic appliances (C)</td><td>2. Small household appliances</td><td>50%</td><td>70%</td><td rowspan="9">Consider weighted average</td><td rowspan="9">Consider weighted average</td></tr>
<tr><td>3. IT and telecommunications equipment</td><td>65%</td><td>75%</td></tr>
<tr><td>4. Consumer equipment</td><td>65%</td><td>75%</td></tr>
<tr><td>5. Lighting equipment</td><td>50%</td><td>70%</td></tr>
<tr><td>6. Electrical and electronic tools</td><td>50%</td><td>70%</td></tr>
<tr><td>7. Toys, leisure and sports equipment</td><td>50%</td><td>70%</td></tr>
<tr><td>8. Medical devices</td><td>-</td><td>-</td></tr>
<tr><td>9. Monitoring and control instruments</td><td>50%</td><td>70%</td></tr>
<tr><td>10. Automatic dispensers</td><td>75%</td><td>80%</td></tr>
<tr><td>Gas discharge lamps (D)</td><td>5. Lighting equipment</td><td>80%</td><td>-</td><td>80%</td><td>-</td></tr>
<tr><td rowspan="2">CRT televisions and monitors (E)</td><td>3. IT and telecommunications equipment</td><td>65%</td><td>75%</td><td rowspan="2">65%</td><td rowspan="2">75%</td></tr>
<tr><td>4. Consumer equipment</td><td>65%</td><td>75%</td></tr>
</table>

The following issue highlights the need to have a common methodology to calculate reuse/recycling and recovery rates. In some cases, different countries in EU have different

interpretations for the same operational practice regarding the quality requirements and the classification of final destinations. For example, the operation of backfilling involves material fractions obtained from the processing of waste that cannot be recycled and are used to fill abandoned mines: in countries like Germany this is classified as a recovery operation, considering that the material fraction is being used to replace other materials that otherwise would have to be used to fill the mine, while in Portugal this is classified as an elimination operation, similar to landfill disposal.

Having different national policies on the management of the WEEE hampers the effectiveness of recycling policies. Therefore, the essential criteria should be laid down at the level of the UE and minimum standards for the treatment of WEEE should be developed, including recovery, recycling and preparing for reuse. According with the WEEE Recast, the EU Commission shall request the European standardization organizations to develop European standards reflecting the state of the art for the treatment, recovery, recycling and preparing for reuse of the WEEE. Subsequently, the EU Commission may set these as minimum quality standards to be implemented in all EU Member States. In this context, the WEEE Forum has been developing a project laying down standards with respect to collection, treatment and recovery of WEEE and monitoring the companies that do these operations (WEEE Forum, 2008b).

The application of the EPR principle to WEEE set the responsibility of producers of electrical and electronic equipment to establish WEEE management systems, to finance the collection and the treatment, recovery and disposal of WEEE and ensure the compliance with designated legal targets. The establishment of producer responsibility should also encourage cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating reuse, dismantling and recovery of WEEE, its components and materials (European Commission, 2012a). In this context, the European Union has also been particularly active in promoting the reduction of environmental impacts resulting from the use of hazardous substances in electrical and electronic products. The EU Directive 2002/95/EC of 27 January 2003 on the restriction of the use of certain hazardous substances in EEE (also known as the RoHS Directive) and its following amendments have been the outcome of the EU policy on the reduction of environmental impacts from the electronics industry. The RoHS Directive imposes bans on the use of hazardous substances on EEE put on the market from 1 July 2006, although with exemptions for some applications (Annex of the RoHS Directive, e.g. Lead in automotive electronics). The ban includes the following substances: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE).

The Directive 2005/32/EC (also known as Directive on Energy using Products, EuP) established a framework for the setting of ecodesign requirements for energy using products amending Council Directive 92/42/EEC (efficiency requirements for hot-water boilers). The recent recast version, the Directive 2009/125/EC (also known as Directive on Energy-related Products, ErP) (European Commission, 2009), addresses a broader range of energy-related products which represent a significant volume of sales and trade, involve a significant environmental impact, and present a significant potential for improvement. This Directive presents a framework for defining specific ecodesign requirements for products recognizing that action should be taken

during the design phase of energy-related products, since it appears that the pollution caused during a product's life cycle is determined at that stage, and most of the costs involved are committed then (European Commission, 2009).

1.1.2 Portuguese legal framework

The European Union Member States, including Portugal, have transposed the previously referred Directives to their national law and, in general terms, there is a common legal framework over EU countries' on the management of waste electrical and electronic equipment.

In Portugal, there are two main Decree-laws that establish the legal framework for the management of WEEE, as follows:

- Decree-law n.º 178/2006, of 5th of September, altered by Decree-law n.º 73/2011, of 17th of June, on the management of waste (Governo de Portugal, 2006a);
- Decree-law n.º 230/2004, of 10th of December, regulating the management of WEEE and the restriction on the use of certain hazardous substances in electrical and electronic equipment (Governo de Portugal, 2004).

The first Decree-law establishes the general framework applicable to the prevention, production and management of waste. This diploma defines a set of principles that constitute the pillars of waste management in Portugal, applicable to all waste streams, including waste electrical and electronic equipment. The principle of protection of human health and the environment is consecrated with the priority objective of avoiding and minimizing the risk to human health and to the environment, by ensuring that the production, collection, transportation, storage and treatment of waste are done using the appropriate methods and/or processes that are not susceptible to harm the environment.

Another pillar is the extended producer responsibility principle, which attributes the responsibility to the producer on the management of waste generated from the products it placed on the market. This responsibility is only legally fulfilled when waste is delivered to a waste management operator specifically licensed by the competent public authorities. In the case of specific waste flows such as WEEE, the responsibility is only fulfilled by transfer to an individual or collective take back system.

The principle of waste hierarchy is also consecrated in the diploma and it establishes prevention and minimization of waste as the priority actions, followed by the waste management destinations of reuse and preparation for reuse, recycling, other forms of recovery and elimination. An exception is defined for specific waste flows including the WEEE, where the hierarchy of destinations may be changed, as long as the adopted order is justified considering the environmental impacts in a life cycle perspective.

Regarding the operational management of waste, all operations that are to be executed (e.g. collection, storage, treatment, reuse, recycling, recovery and elimination) have to be licensed by the competent public authorities and are subject to technical standards. The diploma

establishes the procedures and the attributes of each of the stakeholders, including the operators as well as the competent authorities involved in the process of licensing.

The Decree-law also establishes the reporting requirements that producers of products and producers/holders of waste have to fulfil, as well as the financial regime of waste management that includes a fee for licensing a collective take back systems for specific waste flows (25.000 euros) or a fee due for waste that is managed by take back systems and is not reused, recycled or recovered (2 euro per ton) (Governo de Portugal, 2006a).

Specifically regarding waste electrical and electronic equipment, the Decree-law n.º 230/2004 transposes the WEEE Directive to the Portuguese national law. Its primary goal is to prevent and minimize the production of WEEE and subsequently promote its reuse, recycling and other forms of recovery, to minimize the amount and hazardousness of waste to be eliminated.

The diploma also transposes the RoHS Directive to the Portuguese national law, determining restrictions on the use of certain hazardous substances on electrical and electronic equipment, including other general principles on ecodesign to facilitate reuse, dismantling and recovery of the WEEE, its components and materials.

The Decree-law n.º230/2004 is applicable to waste from electrical and electronic equipment classified in ten legal categories (see Annex I), including all components, sub-assemblies and consumables that are part of the equipment when it is discarded. All equipment that do not fit in the referred categories or equipment for military use are excluded from the scope of the diploma.

The principle of extended producer responsibility is behind the legal framework for WEEE in Portugal. According with Decree-law n.º 230/2004, producers of EEE are responsible for the management of WEEE respective of the products they place on the market. Additionally, producers have to support the management of historical WEEE (from EEE put on the market before 13th of August 2005, according with the WEEE Directive) in the proportion of the respective market share.

All stakeholders in the life cycle of electrical and electronic equipment, including the producers, distributors, waste management operators, waste producers/holders and public authorities are co-responsible for the management of the WEEE and have a role to play to ensure its proper collection, treatment and recovery. However, it is the producers of EEE, including manufacturers and importers that are liable to develop individual or collective take back systems, set up the infrastructure and finance the collection, treatment and recovery operations.

In Portugal, producers of EEE have to provide for the adequate means to ensure that holders of WEEE throughout the country, including the continental territory and the archipelagos of Madeira and Azores, can safely deliver the WEEE free of charge. Such requirement entails the producers or the representing PRO, to develop infra-structure for WEEE collection in the entire country. This is an important part of the WEEE management system in order to fulfil the legally established collection target of 4 kilograms per inhabitant per year of WEEE from households that is currently in force and should be applicable until the end of 2015, according with the requirements of the WEEE Recast directive that is yet to be transposed in to the Portuguese

legal framework. Considering the population of Portugal the collection target amounts to approximately 41.000 tons of WEEE from households.

The Decree-law n.º 230/2004 also establishes minimum selective treatment requirements for WEEE, including the mandatory removal of certain hazardous substances and components listed previously, as well as the treatment of CRT with the removal of the fluorescent coating, for equipment containing gases that are ozone depleting or have a GWP above 15 the gases have to be extracted and treated, and for gas discharge lamps the mercury has to be removed.

For all the WEEE that is collected and treated, the producers or the respective PRO, have to ensure minimum percentages of reuse/recycling and recovery. Such targets are defined per category of electrical and electronic equipment, in the same way as the WEEE Directive does and that was already explained. In the context of the Portuguese national law, the challenges regarding the assessment of the reuse/recycling and recovery targets per legal category also arise, since the operational field data refers to the five WEEE treatment categories.

The reuse/recycling and the recovery targets defined in Decree-law n.º 230/2004 per legal category are presented in Table 1.4. The values are identical to the ones already presented in Table 1.1, with the exception of legal category 8 Medical devices, for which there was no target defined in the WEEE Directive and correspondingly in Decree-law n.º 230/2004.

Table 1.4 – Minimum Reuse/Recycling and Recovery targets in Portugal (Governo de Portugal, 2004)

Categories	**Until 2015**	
	Reuse/Recycling target (%)	**Recovery target (%)**
1. Large household appliances	≥ 75%	≥ 80%
2. Small household appliances	≥ 50%	≥ 70%
3. IT and telecommunications equipment	≥ 65%	≥ 75%
4. Consumer equipment and photovoltaic panels	≥ 65%	≥ 75%
5. Lighting equipment	≥ 50%	≥ 70%
5.1 Gas discharge lamps	≥ 80%	–
6. Electrical and electronic tools	≥ 50%	≥ 70%
7. Toys, leisure and sports equipment	≥ 50%	≥ 70%
8. Medical devices	–	–
9. Monitoring and control instruments	≥ 50%	≥ 70%
10. Automatic dispensers	≥ 75%	≥ 80%

In Portugal the producers of EEE have developed collective systems to fulfil the legal obligations, as in most European countries. The two PRO's responsible for the take back systems in Portugal had to be licensed by the competent public authorities, including the Ministry of Environment and the Ministry of Economy.

According with Decree-law n.º 230/2004, the producers of EEE can transfer their responsibility on the management of WEEE to either one of the PRO's by signing a contract that identifies the characteristics of the EEE involved, the amounts placed on the market, the amount of WEEE to

be collected, the fee due for the transfer of the responsibility and the actions of monitoring the fulfilment of the contractual terms agreed. Article 18 of the legal diploma defines that the PRO's responsible for the take back systems ensure the objectives of collection, treatment and recovery targets, for which the organizations have to:

- Develop an infrastructure to ensure collection and transportation of WEEE in the entire country; this could integrate the municipal collection systems, private waste management operators, logistics operators, distributors and wholesalers, and other;
- Establish an infrastructure to treat and recover WEEE by signing contracts with partners, especially those with certified environmental management schemes;
- Sign contracts with producers of EEE, promoting the transfer of their legal responsibility over the end-of-life management over the electrical and electronic products they place on the market;
- Monitor and control the waste management system, in particular the flows of WEEE from collection points to the processing partners, as well as the materials resulting from processing of WEEE, to ensure the compliance with requirements on the selective treatment of hazardous substances and components (paragraph 1, article 6 of the WEEE Directive) and the achievement of the reuse/recycling and recovery targets legally established (article 7 of the WEEE Directive);
- Promote the research and development of new methods and tools for the management of WEEE, by providing financial and technical support to specific projects;
- Promote public awareness and develop communication campaigns on the adequate management of WEEE;
- Report the activities and the results to the designated national public authority on waste, the *Agência Portuguesa do Ambiente*.

The PRO's also have an important responsibility in promoting ecodesign including to limit the use of hazardous substances in new EEE and facilitate reuse, dismantling and recovery of the WEEE, its components and materials.

The PRO is financed by a financial contribution provided by producers when transferring their responsibility for the end-of-life management of the products they placed on the national market. The financial contribution is determined by applying a unitary fee, generally designated as eco-fee or ecovalue, multiplied by the amount (in number of units or in weight) of EEE placed on the market. The ecovalue is an important part of the management of WEEE and it has to be approved by the APA in order to be applied by the PRO's. The ecovalue has to provide the financial support for the take back system to ensure the collection of the WEEE throughout the country, free of charge, as well as the treatment and recovery of the WEEE, fulfilling the respective legal targets.

Additionally to transferring the responsibility to the PRO, producers of EEE have to register themselves in order to make possible the control and monitoring of the fulfilment of their legal obligations under the Decree-law n.º 230/2004. The producers sign up and provide data on an annual basis to the *Sistema Integrado de Registo Eletrónico de Resíduos* (SIRER), the integrated electronic waste registry system of the national authority on waste, the APA. The competence

over the registry of producers of EEE can be partially or totally allocated to other entities designated by the APA. This has been the case since 2006, when the *Associação Nacional para o Registo de Equipamentos Elétricos e Eletrónicos* (ANREEE), a joint association of producer associations and PRO, was licensed to ensure the registry of producers of EEE in Portugal.

1.1.3 Producer responsibility organizations: scope of intervention and operational targets

Producer responsibility organizations are one of the most common forms of organizations developed by producers of EEE in Europe to fulfil their legal responsibilities on the management of WEEE. The PRO's are not for profit organizations of different legal natures (e.g. associations of producers, private companies, etc.) responsible for the development and implementation of collective take back systems for WEEE, an approach widely adopted in European countries in detriment of individual systems. In Portugal, the producers of electrical and electronic equipment organized in two collective PRO's: AMB3E and ERP Portugal. Both of them are not for profit organizations responsible for the Portuguese national WEEE management system.

In this context, the producers of EEE sign contracts with one of the PRO's and transfer to it the responsibility for the end-of-life management of the electrical and electronic equipment they place each year on the market. The producer informs the PRO of the amount of EEE placed on the market (in weight and number of units) and pays the corresponding fee to support the cost of managing the WEEE.

The PRO's have to be licensed by the competent public authorities. In Portugal, each PRO was jointly licensed by the *Agência Portuguesa do Ambiente* of the Ministry of Environment and by the Ministry of Economy, according with Decree-law n.º 230/2004:

- Joint dispatch n.º353/2006, of 27th of April, of the Ministry of Environment and the Ministry of Economy – License of a management entity of the WEEE integrated management system, *ERP Portugal – European Recycling Platform Portugal, Associação Gestora de REEE* (License ERP Portugal) (Governo de Portugal, 2006b);
- Joint dispatch n.º354/2006, of 27th of April, of the Ministry of Environment and the Ministry of Economy – License of a management entity of the WEEE integrated management system, *AMB3E – Associação Portuguesa de Gestão de Resíduos* (License AMB3E) (Governo de Portugal, 2006c).

The licenses were conceded in 2006 to AMB3E and ERP Portugal, with an expiration date of 31st of December 2011 and including the possibility of renewal. Before the end of 2011, both entities submitted applications to APA for the renewal of their licenses for an additional 5 year period. During this time, the APA has been analysing the applications and the decision so far has been to extend the original licenses for successive periods of three months, maintaining the original conditions. It is expected that with the recent entry into force of the WEEE Recast the APA will develop and concede new licenses incorporating more ambitious requirements.

The licenses establish the responsibilities of the PRO's and the objectives that the organizations have to fulfil, most notably regarding the collection, treatment and recovery of WEEE. These

also establish the scope and the activities for the implementation of the WEEE management systems, including the development of infrastructure, the development of information campaigns and research and development projects.

One fundamental responsibility of each PRO is to develop and implement a nationwide infrastructure that allows holders and producers of WEEE to safely deliver their waste, free of any charge. The PRO's sign contracts with existing waste management operators that are licensed to receive the WEEE and to store it temporarily. In Portugal, the network of such collection centres includes the municipal waste management systems, waste management operators from the private sector and the distributors. By doing this and also by developing campaigns and other initiatives to inform the waste holders and the general public, the PRO's contribute to the national collection target of 4 kilograms per inhabitant per year.

The license also assigns that each PRO individually has to contribute annually to the collection target in the percentage respective of the market share (in weight) of the producers that have transferred their responsibility. As an indication, both licenses originally established a minimum amount of WEEE to be collected by each PRO based on an estimated market share in weight of 80% for producers associated with AMB3E and 20% for producers associated with ERP Portugal. The effective annual collection target for each PRO is established at the end of respective year based on the market share information provided by the registry entity ANREEE.

The PRO's are also responsible to ensure the selective treatment of all the WEEE that is collected, including the removal of hazardous substances and components as listed in the Annex II of the WEEE Directive and Decree-law n.º230/2004, and to fulfil the minimum reuse/recycling and recovery targets already mentioned in the previous section. In order to do so, the PRO's signs contracts with end-of-life processing partners, which include waste management operators from the public and private sectors, that have the personnel and the technologies to process the WEEE, by removing the hazardous substances and components and also separating the materials for recycling and other forms of recovery.

The WEEE is transported from collection centres to the end-of-life processing facilities by logistics operators with which the PRO's also sign contracts. One of the most important jobs of the PRO's is to assign a destination for each batch amount of WEEE that has been collected and is in storage in the collection centres. There can be hundreds of batch amounts of WEEE allocated and transported each year from collection centres to processing operators. This can have significant impacts on the results of waste management at the end of the year, namely regarding the fulfilment of the legal targets on reuse/recycling and recovery as well as on the economic and environmental performance of the entire WEEE take back system. Consequently, the allocation of the amounts of collected WEEE to the specific end-of-life processing operators should be done considering the best alternative technologies and their performance considering the technical, economic and environmental aspects.

Figure 1.1 presents a schematic view of the stakeholders involved in the EPR based systems to manage the WEEE and the respective flows of mass, information and money.

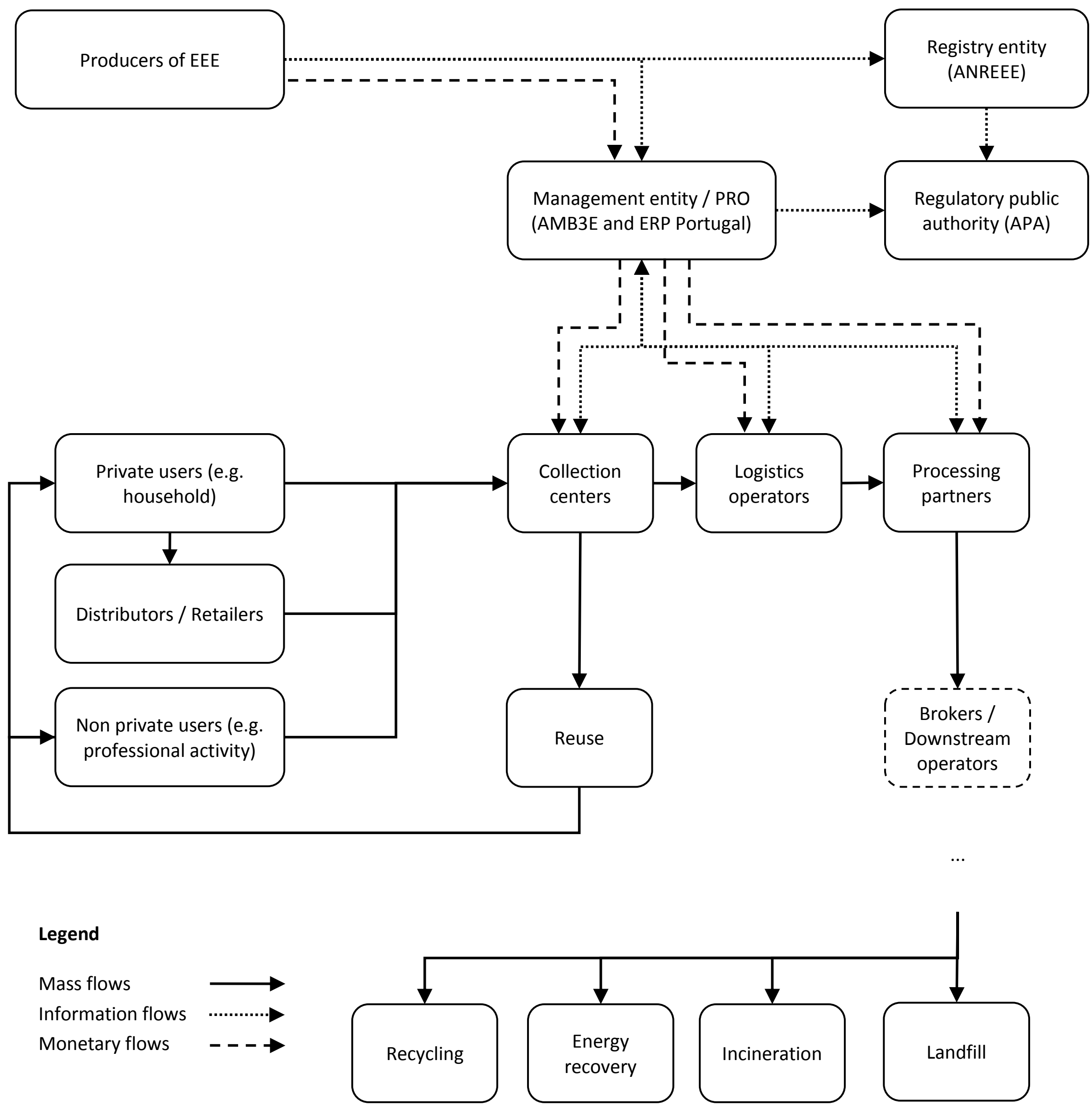


Figure 1.1 – EPR based WEEE management system

The waste flows from the producers and/or holders, including private and professional activities, and is delivered at collection centres. Here, it is legally required that the producers of EEE ensure that the delivery is done free of any charge for the producer/holder of WEEE. Usually, the PRO's provide financial assistance for collection centres to execute sorting operations, to segregate the WEEE in the five treatment categories that match the specifications of the subsequent treatment technologies. The financial support to the collection centres is also intended to cover for the burden of reporting the information on the collected WEEE to the PRO's.

The WEEE sorted and stored is then loaded in to trucks and transported by logistics operators to a designated processing partner, according with instructions from the PRO. The end-of-life processing partner receives the WEEE in its facilities and processes it using the technologies that provide the removal of hazardous substances and components, as well as the separation of materials for recovery. The producers of EEE are legally responsible for financing the treatment

and recovery of WEEE (European Commission, 2003b). The economic balance of WEEE treatment and recovery is difficult to assess and depends on several conditions, such as the cost of processing and the price of secondary materials for recycling. Most documented cases (United Nations University, 2007) seem to indicate that the overall economic balance has a negative value and so the PRO's have to provide financial assistance for processing partners. However, with the increase in prices of secondary materials and the development of new technologies to recover additional materials and economic value from WEEE, the trend is for the economic balance of WEEE treatment and recovery to increase.

The contractual framework of the PRO's is limited to the first tier end-of-life processing operators. However, the mass flows proceeds, with the substances, components and materials that resulted from the treatment and initial processing being sent to subsequent operations to be processed before eventually being sent to final operations of recovery or elimination. Besides the operators that do the additional processing and the final operations, there can be other types of stakeholders that intervene after the contractual framework of the PRO's, and those are the brokers. These are organizations that essentially promote the trade, bridging the supply and demand, without having any physical intervention on the waste or material fractions. This activity has only recently been regulated by Directive 2008/98/EC, which recognizes the role of such organizations within the waste management chain (European Commission, 2008).

In order to support the WEEE management system, including the structural and operational costs, the PRO's are financed by producers. The unitary financial contribution, eco-fee or ecovalue, is determined by each PRO individually and has to be approved by the competent public authorities. The ecovalue also has to provide for the financing of the PRO's activities regarding the development of information campaigns and research and development projects. According with the license, each PRO in Portugal has to develop or provide financial support for the development of campaigns to inform and raise awareness of waste producers/holders, other stakeholders involved in the system (e.g. waste collection operators, logistics operators, processing partners) and the general public on the importance of the issues of WEEE management and their possible contributions to improve it. For this matter, the license establishes a minimum investment of 5% of total annual income.

Recognizing the importance of the development of new treatment and recovery technologies to increase the efficiency and the effectiveness of WEEE management, PRO's have to execute and/or support the development of research and development projects. In Portugal, PRO's have to ensure a minimum investment of 3% the total annual treatment costs to support research and development projects.

According with requirements from the license, the PRO's report periodically to the WEEE management system's governing body, the APA, providing information on the activities done and the results obtained, including the assessment of the compliance with the legal targets.

1.1.4 Contribute of EPR to the WEEE management in Portugal

The overall amounts of WEEE collected in Portugal by AMB3E and ERP Portugal have been increasing. Since 2008 the country has achieved the legal collection target. From Figure 1.2 it is possible to verify that in 2011 AMB3E and ERP Portugal collected together more than 50000 tons of WEEE, representing approximately 5 kilograms per inhabitant per year.

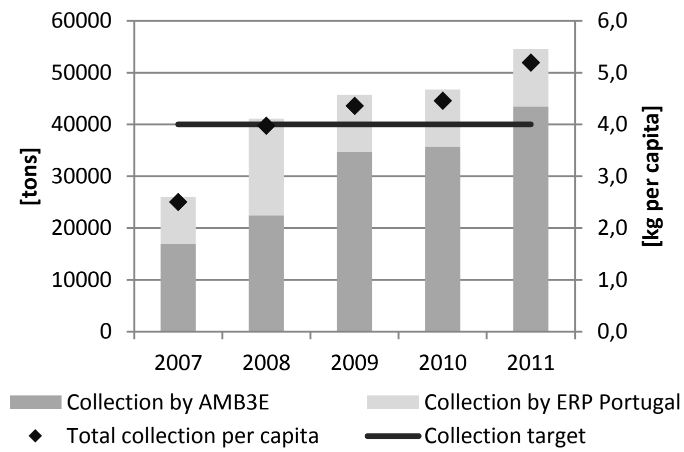


Figure 1.2 – Evolution of WEEE collection in Portugal (AMB3E, 2006, 2007, 2008, 2009, 2010, 2011 and ERP Portugal 2011)

The amount of WEEE collected by AMB3E and ERP Portugal represents only about half of the estimated total amount produced in the country (Governo de Portugal 2006b and 2006c). The remaining WEEE is collected by the informal sector and treated as metal scrap (e.g. metal dominated products like large household appliances and cooling and freezing appliances) or discarded by consumers as municipal solid waste (e.g. small domestic appliances, lamps and CRT televisions and monitors) (Agência Portuguesa do Ambiente, 2010).

Over the years, the PRO's have developed networks of partners for end-of-life processing of the WEEE to ensure the de-pollution of the discarded equipment and its reuse, recycling and recovery. Despite the positive developments, there are still systemic inefficiencies that affect the recovery of the WEEE. In fact, Portugal still shows a limited performance towards a "recycling society", with "medium/low levels of recycling" and "high levels of landfill disposal and a static or increasing reliance on this method of treatment" (Institute for European Environmental Policy et al., 2010).

The results made public by the PRO's indicate that the EPR based systems in Portugal have certainly provided improvements in terms of collection, recycling and recovery performances for WEEE. In this context, it is possible to state that PRO's and the waste management systems they run have been so far, a step forward towards developing a "recycling society" in Portugal. Still, there is room to improve the performance of current EPR based systems addressing the management of WEEE.

1.1.5 Key challenges for the development of environmentally and economically optimized PRO's

A decade after the publication of the WEEE Directive and the comprehensive development of WEEE collective take back systems, there is still a growing need to increase the recovery of material resources incorporated in discarded electrical and electronic products and to reduce the environmental contamination from hazardous substances. The recent WEEE Recast presents more ambitious legal requirements on collection and reuse/recycling and recovery of the WEEE, which demands greater effectiveness in the management of this specific waste stream and may represent an increase in the financial resources necessary. Combining this with the macroeconomic situation prevalent in Europe since 2008, which has been negatively affecting sales of electrical and electronic equipment and consequently the revenue of PRO's originating from the ecovalue, there is presently an increased risk to the economic balance of WEEE management systems. The PRO's are forced to respond by increasing the efficiency of the WEEE management systems. On the other hand, perspectives over the increase in demand for secondary materials, the most recent and notorious example of rare earth metals, and on the development of more efficient end-of-life technologies present the opportunity to generate technical, economic and environmental benefits to the management of WEEE (European Commission, 2010).

As the PRO's accept the legal responsibility transferred by producers of EEE for the collection, specific treatment and recycling of WEEE necessary to achieve a high level of protection of human health and the environment (European Commission, 2003b), these organizations assume a leading role in defining how the WEEE is managed presently and will be in the future, from the technical, economical and environmental perspectives. From the technical standpoint, the PRO's have to fulfil the legal targets on collection, treatment and recovery. From the economic point of view, PRO's have to comply with all legal requirements established in their licenses at the minimum cost possible, in order to minimize the ecovalue for the associate producers and be more competitive than other PRO's operating in the same country. From an environmental perspective, the PRO's have to minimize the impacts on the environment and on human health resulting from the WEEE management.

Considering the generic activities in a WEEE take back system in Europe, one can split the administration of the system done by the PRO's from the operations including the collection, transportation, treatment and recovery done respectively by the collection facilities, the logistics operators and the processing partners. When analysing the contribution of the different activities to the overall performance of the systems, in general the operational management is critical to determine the total technical, economic and environmental performance. The administration activities in general have a decisive but negligible contribution.

First of all, from a technical perspective, the collection infrastructure is critical for the PRO's to collect the WEEE and comply with the respective legal target. WEEE collection is increased by developing appropriate collection facilities with attributes such as the close proximity to households, high working time and number of days in service throughout the year and the minimization of any recycling fee (Bouvier and Wagner, 2011). The logistics network is critical to

transport the collected WEEE to the treatment and recovery facilities, which in turn are decisive for the PRO's to ensure the specific treatment and recovery of WEEE. This stage is entirely responsible for the ability of the PRO's to comply with the legal targets on reuse/recycling and recovery.

From an economic perspective, the operational management is most significant also. For instance, as a result of the implementation of the WEEE Directive in Europe, the average cost of collection including the financing of collection centres and the transportation of WEEE to treatment facilities represents approximately 32.4% of the total WEEE management cost (adapted from United Nations University, 2007), while the cost of treatment and recovery accounts for approximately 50.5% of the total cost (adapted from United Nations University, 2007). The activities of administrating the system represent on average 17.1% of the total cost of the WEEE management (adapted from United Nations University, 2007).

From an environmental perspective, the contribution of the operational management is even more striking. WEEE management has environmental burdens that surpass the gains (adapted from United Nations University, 2007). Considering that there are five different treatment categories of WEEE, the collection can represent between 6.5% and 16.1% of the total environmental burdens of the WEEE management, while the treatment and recovery represent between 83.9% and 93.5% (adapted from United Nations University, 2007). The entire environmental gains of the WEEE management come from treatment and recovery operations, although these would not be possible without all of the preceding collection and other activities (adapted from United Nations University, 2007). The contribution of the administration activities to the WEEE management's environmental performance is negligible.

In this context, the development of an efficient collection infrastructure and logistics network, linking the collection centres to the treatment and recovery facilities is an important part of the PRO's activities and can have significant contributions to improve the sustainability of the WEEE management system. This subject has already been the focus of research, in particular for the Portuguese WEEE management system (Ferreira, 2011, Gomes et al., 2011) and was not addressed in the research work presented in this document.

Likewise, the development of a network of end-of-life processing partners for WEEE is also an important part of the PRO's activities in the implementation of a take back system and can have even more significant impacts on the overall technical, economic and environmental performance of WEEE management.

The treatment and recovery of high volumes of WEEE collected by the WEEE management system requires the use of industrial scale technologies, with high processing capacity and relative low cost. In European countries these technologies include a combination of manual and mechanical operations, which are owned and operated by waste management operators, from the private and public sectors. By the time the WEEE Directive was developed in the early 2000's, there was some underdevelopment of the WEEE treatment and processing sector in Europe and particularly in Portugal in terms of the number of operators and the performance level of the technologies. This situation posed significant challenges for the development of the WEEE management systems, namely regarding the capability to treat and process the amounts

of WEEE that were collected and achieve high performance levels required to fulfil the legal targets on reuse/recycling and recovery. Over the years, the establishment of PRO's and the implementation of WEEE management systems in Europe helped to develop the WEEE processing industry, mostly as a result of the stable provision of input material and the financial support provided to the operators (Niza et al., 2013).

Despite the systemic and technological developments, global problems in recycling WEEE still remain, most notably in the lack of technologies and the misuse of those currently available to handle the complex electrical and electronic equipment that are discarded. One of the main reasons pointed out in research for this is the fact that the know-how on recycling WEEE, the technologies and their use, is still mostly owned by the recyclers (Kuo, 2010). The PRO's lack the knowledge on the recycling of WEEE to take full advantage in the development of their networks of processing partners, or even to foster the development of new technologies. One possible reason for this may come from PRO's signing contracts with operators acting as service providers, from whom it is required the presentation of a result of treatment and recovery of WEEE, but in fact little is done to monitor and assess the effectiveness of such result. The fact remains that the unavailability of knowledge on the end-of-life technologies is a barrier for the efficient and effective management of WEEE and consequently optimizing product recovery is often hindered (Zuidwijk and Krikke, 2008).

The scope of the knowledge is also important. In European WEEE management systems the PRO's sign contracts only with first tier operators and not with downstream operators along the entire end-of-life processing chain. The PRO's only monitor the activities and the performance of the first tier operators and use basic data to assess the performance of WEEE management, namely regarding specific treatment and to calculate the reuse/recycling and recovery rates (e.g. amount of input WEEE, output material fractions and the respective classification of the subsequent operation – recovery of disposal (European Commission, 2000) – that will take place in the second tier operator). Although it can be argued that this approach is necessary to respond to the complex nature of the WEEE processing, it translates a simplification of the effective result obtained at the end of the WEEE processing chain, as in essence it is a chain of operations done by processors in different levels, often installed in different countries and different continents (Widmer et al., 2005).

It becomes necessary to assess and take in account the performance of all the individual processing steps and processors from the beginning until the end of the end-of-life processing chain in order to accurately measure the reuse/recycling and recovery rates. The same can be said for the accurate assessment of the economic and environmental performance of WEEE management. It is essential that PRO's are able to make knowledgeable decisions which they can be sure of its effects and thus take the management of WEEE in the right direction and improve the technical, economic and environmental performance.

If producers are to fully take on their legal responsibilities to achieve a high level of protection of human health and the environment according with the requirements of the WEEE Directive, they have to improve the technical, economic and environmental performance of the treatment and recovery of WEEE. In order to do so, the PRO's have to develop in-depth knowledge on the existing end-of-life technologies and their use throughout the entire end-of-life processing chain

and take it in consideration when selecting the alternative processing technologies and partners that should integrate their network and when allocating to them the amounts of collected WEEE to be treated and recovered.

The PRO's should also make use of the knowledge to identify the need and opportunity to support research and development projects for new processing and recycling technologies and to support the implementation of ecodesign, namely to incentivize the producers of EEE to design the products in view of facilitating reuse, dismantling and recovery of WEEE, its components and materials. In this context, the research presented in this document focused on two fundamental challenges:

- Develop and make available useful knowledge on the technical, economic and environmental aspects of the technologies used to treat and recover WEEE throughout the entire end-of-life processing chain;
- Use the knowledge to improve the technical, economic and environmental performance of the WEEE treatment and recovery.

In the following section the state of art of research in WEEE management is characterized, in particular regarding the main topics where mathematical models have been developed and applied to improve the performance.

1.2 State of the art of WEEE processing models

In the early days before there were specific legal obligations on the management of WEEE, several EEE producers set up their own networks to manage the waste returns (Ayres et al., 1997). In most cases this was motivated by the economic value of the WEEE as well as the risk of damage to the environment of some products when they reached the end-of-life. In parallel, the tremendous benefits that can be derived from the proper recovery of WEEE have also prompted the scientific community's interest in research on the subject, and has since then been working with the producers in the development and improvement of the WEEE management.

In this context, many topics of research have been addressed, from the development of WEEE processing technologies, to their transfer and use, to the design and development of WEEE management systems and the assessment of impacts as well as the improvement of the performance in the WEEE value chain. Of particular interest for the present thesis has been the research and development done on mathematical models and the conduction of several surveys and applications to study the take-back and recovery systems. For example, the WEEE management system in Holland is analysed based on the environmental benefits and costs (Stevels, 1999) and in particular for the WEEE category of large household appliances (de Koster et al., 2005). The WEEE management systems in other countries have also been studied, including Germany (Walther et al., 2005), Denmark (Braun et al., 2005), Sweden (Nagel et al., 1999), Switzerland (Hischier et al., 2005; Streicher-Porte, 2006; Khetriwal, 2009), Italy (Gamberini et al., 2010), Scotland (Feszty et al., 2003), Greece (Achillas et al., 2010; Achillas et al., 2012), Finland (Ylä-Mella et al., 2004; Lehtinen and Poikela, 2006), Romania (Ciocoiu et al.,

2010; Torretta et al., 2013), China (He, 2006; Kojima et al., 2009), Taiwan (Chien et al., 2007) and also Portugal (Luízio, 2004; Gomes et al., 2011; Machado et al., 2010; Niza et al., 2013).

Other research work addressed the end-of-life management of single product types, essentially based on some producers own individual initiatives. Several case studies regarding the end-of-life of electrical and electronic products are presented by Flapper et al. (2005) and by other authors, including copier machines by Zuidwijk et al. (2005), cellular phones by Guide et al. (2005), large household appliances and consumer electronic goods by de Koster et al. (2005). Similar works have been published addressing other individual types of electrical and electronic products: refrigerators (Krikke et al., 2003), monitors, scanners and laptops (Sharma et al., 2007), copier machines (Thierry et al., 1995; Krikke et al., 1999; Fleischmann et al., 2001), printers (Mayers et al., 2005), computers (Nagel and Meyer, 1999), home appliances (Shih, 2001), among others.

The literature review showed that most scientific surveys and mathematical models have concentrated on the following areas:

- Design of WEEE collection and recovery networks, regarding the location of sites and the allocation of WEEE amounts;
- Assessment of technical, economic and environmental performance of WEEE management;
- Definition of strategies for end-of-life processing and optimization of the sequence of operations to enhance recycling and promote ecodesign.

With the publication of the WEEE Directive, since 2002, all producers of EEE in EU member countries are legally obliged to establish WEEE management systems, to collect and recover all types of WEEE put on the market. The design of networks for collection of used products and for their recovery has attracted the interest of many researchers, mainly motivated by economic, legal and customer oriented objectives. A survey of papers proposing mathematical models for the design of collection and recovery networks developed in a wide variety of countries is presented in Gamberini et al. (2008).

Similar to the case of distribution networks (Fleischmann et al., 1997; Manzini et al., 2007), the design of WEEE collection networks can be tackled by taking on three different perspectives: long, medium and short term-oriented. In the first case, the research deals with the problems of defining the facilities that belong to the network, their responsibilities and the allocation of their resources. In a medium term perspective, the research addresses the problem of defining the strategies for planning activities in an already existing network by optimizing the performance for specific indicators. Finally, in a short term perspective, the research establishes the optimized schedule of the various operations in the recovery process.

A significant number of studies address the location-allocation problem (Kroon and Vrijens, 1995; Spengler et al., 1997; Barros et al., 1998; Louwers et al., 1999; Shih, 2001; Jayaraman et al., 2003; Listes and Dekker, 2005; Min et al., 2006; Lieckens and Vandaele, 2007). The problem of managing an already existing collection network is dealt in Hu et al. (2002), El-Hamouz (2008) and Gamberini et al. (2008) by optimizing medium term performance indicators. The operations

of WEEE closed-loop supply chains are also studied using location and allocation problems (Walther et al., 2005; Krikke et al., 2003; Shih, 2001).

The literature review shows some important gaps in research. First of all, most attention has been given to the development of collection networks and far less to the development of recovery networks. It is almost as if the assumption has been made that if the waste is collected it is recovered. Additionally, the research on the development of collection or recovery networks has been often severed in geographical terms, as many studies focus a sample of a countries' territory. The same happened regarding the scope of products, as studies address specific categories or even single product types. Both kinds of situations are not consistent with the WEEE management systems, which cover the entire national territories and operate the collection, transport and recovery of all WEEE categories.

Some example are found in Gomes et al. (2011) when they research the best locations for collection and sorting centres in Portugal. Queiruga et al. (2008) studied the best location for WEEE treatment plants in Spain. The study was conducted for one of the nationwide systems that exist in the country to collect products from all WEEE categories. The authors developed a method to produce a classification of Spanish municipalities regarding how adequate it would be to install the plants, considering economic, infrastructural and legal criteria. Walther et al. (2008) focused on facility location planning for the treatment of WEEE category large household appliances, while Franke et al. (2006) presented a capacity and facility adaptation planning model for remanufacturing a specific product type, mobile phones. The most common WEEE product categories which are studied are the refrigerators (Lambert et al., 2001; Stoop et al., 1998; Krikke et al., 2003; Bloemhof-Ruwaard et al., 2004; Umeda et al., 2000), personal computers (White et al., 2003), mobile phones (Stutz et al., 2002) and electrical brooms (Dowie, 1994).

The location of treatment facilities for WEEE in Greece is studied by Achillas et al. (2010). In the research, a methodology is developed to optimise the reverse logistics network for WEEE and a mathematical model is formulated taking into account the existing infrastructure of collection points and recycling facilities and considering social and economic aspects. The applicability of the developed model is demonstrated by employing a case study for a limited geographical area, the region of Central Macedonia, in Greece.

The assessment of technical, economic and environmental performance is transversal to all research topics regarding the WEEE management. Initially, most research work focused on these aspects individually. More recent work has started to address the various aspects. Still, gaps have been made evident in the lack of joint assessment and multiple objective improvement of WEEE management in technical, economic and environmental aspects.

The majority of the mathematical models developed on the WEEE subject estimate the total cost and or profit of the operations of the end-of-life processing chain (Qian et al., 2003; Spengler et al., 2003; Feszty et al., 2003; de Ron et al., 1995; Krikke et al., 2003; Atasu et al., 2009; Bloemhof-Ruwaard et al., 2004). Other models address either the environmental costs of the recovery of WEEE (Qian et al., 2003; Lambert et al., 2001) or its environmental impacts (Hischier et al., 2005; Stoop et al., 1998; Kleijn et al., 1999; Umeda et al., 2000). For example, a

simulation model is presented by Kara et al. (2003 and 2007) which calculates collection costs for WEEE in the metropolitan area of Sidney, Australia.

The objective of managing both technical and environmental performance indicators is introduced by Hirsch et al. (1998). Other studies by Nema and Gupta (1999), Krikke et al. (2003), Georgiadis and Vlachos (2004), Hugo and Pistikopoulos (2005), Duque et al. (2007) and Hanafi et al. (2008) propose models for designing recovery networks with the target of optimizing costs and the environmental risks associated to the activities in the end-of-life processing chain. Duque et al. (2007) propose a model in order to optimize the collection network structure under both design and environmental constraints. Hanafi et al. (2008) integrate a forecast model with a collection network model to allow government organizations or manufacturers to choose the best collection strategy considering both economic and environmental performance.

Other authors, Gamberini et al. (2010) present an integrated approach for management strategies of existing WEEE collection networks considering both technical and environmental objectives. Specifically, input data are initially collected, then different system scenarios are generated and assessed and finally the best one is identified addressing technical and environmental performances. As regards the technical and operative performance measures, such as cargo capacity and working day saturation, they are obtained by means of simulation. The lack of experimental field data is a common feature of research work in this area and often becomes a limitation.

Regarding the environmental assessment of end-of-life scenarios, the Life Cycle Assessment (LCA) methodology is generally adopted, as this is a valid tool for comparing the environmental performances of distinct WEEE management alternatives (Bovea and Powell, 2006). In fact, several authors (Bloemhof-Ruwaard et al., 1995; Azapagic, 1999; Azapagic and Clift, 1999; Alexander et al., 2000; Hugo and Pistikopoulos, 2005) state the effectiveness of the LCA applied to network management solutions.

Besides studying the characteristics of the WEEE take back and recovery systems, many surveys have concentrated on end-of-life strategies. Mathematical models have played an important role in the research of end-of-life planning problems, as it is demonstrated in the studies done by Gungor and Gupta (1999), Fleischmann et al. (1997) and Goggin and Browne (1998). Regarding product recovery and recycling, a number of investigations have considered important aspects of the optimization problem. For instance, Johnson and Wang (1998) presented a systematic procedure of generating disassembly sequences to maximize the economic gains from material recovery. Penev and de Ron (1996) described a cost modelling tool to determine the economically viable level of disassembly and the respective sequence for a specific product. Goggin and Browne (2000a) described a decision support software model to identify the best route considering the economic cost and value balance. Lambert (1997) developed a linear optimization model for an optimum disassembly of complex products. Pnueli (1997) suggested an algorithm to solve the disassembly sequencing problem that includes the end-of-life value of a product.

Research works done by Kuo et al. (2001), Deasi and Mital (2003) and Sodhi et al. (2004) have focused on design for disassembly strategy which allows for the separation and use of recycled

materials in substitution of virgin ones. Ferrão and Amaral (2007) described a design for recycling tool that provides the identification of economically optimum recycling strategies aimed at achieving given recycling and reuse rates by combining dismantling, shredding, and post shredding activities.

A significant number of the models address only specific parts of the WEEE end-of-life processing chain, and they generally lack the capability to analyse the entire chain. Specifically, Neto et al. (2007) examine different end-of-life recovery strategies by assessing the respective environmental benefits, focusing particularly on waste reduction and energy and virgin materials savings. Cui and Forssberg (2003) deal exclusively with the mechanical recycling of WEEE, while White et al. (2003), using a case study from the computer and electronics industry, highlight the challenges that the decision makers face to recycle the products, regarding the collection of used products and the disassembling process.

The publications that deal with decision support systems for WEEE recycling show that the research mainly provides the assessment on a macro level, for WEEE entirely as one waste stream, in the different technical, economic and environmental aspects. For example, Lamvik et al. (2002) presented an end-of-life methodology of product systems to determine the most appropriate option - reuse, material recycling, incineration or landfill disposal - based on economic, environmental and social aspects. Rose et al. (1999) present a design oriented decision framework which focuses on technical product design variables such as expected life time and number of parts to select an appropriate end-of-life strategy at the design stage. On the other hand, Goggin and Browne (2000b) describe a taxonomy of electrical and electronic manufacturing situations from a resource recovery perspective to provide an understanding of the recovery and recycling issues.

A lower level assessment is important in defining end-of-life strategies, distinguishing the different categories of WEEE that have distinct characteristics and therefore can have specific individual end-of-life strategies. Nevertheless, it is critical to always take in consideration the interactions between different WEEE categories in the global WEEE management performance, and integrate them in order to jointly improve the technical, economic and environmental indicators. Stoop and Lambert (1998) show that recycling of refrigerators should be based on an integral approach, aiming at maximum elimination of chlorofluorocarbon, high recovery of metals and low input of energy, whereas Umeda et al. (2000) suggest that the material and energy consumption of EEE can be reduced drastically without decreasing corporate profits by appropriately combining product maintenance, reuse and recycling. Hischier et al. (2005) confirm that WEEE recycling is clearly advantageous from an environmental perspective compared to the scenario where no WEEE is recycled. Kleijn et al. (1999) estimate the environmental impact of the WEEE closed-loop supply chains from the extraction of raw materials to the WEEE recovery.

The research work behind the present thesis addressed the key challenges regarding the development of environmentally and economically optimized PRO's and simultaneously tried to fill in some of the main gaps identified in the literature review.

1.3 Research objectives and questions

The fundamental objective of the present thesis was to develop a model of the end-of-life processing and recovery infrastructure for WEEE and use it to improve the performance of the WEEE treatment and recovery considering the technical, economic and environmental aspects. A case study was developed for the Portuguese infrastructure and included the downstream operations. The research focused on extensively characterizing the industrial processes throughout the entire end-of-life processing chain for WEEE, considering the technical, economic and environmental aspects. Based on the leading role of PRO's in the management of WEEE, the following research questions were developed:

- How can technical/economic models be developed in order to successfully characterize the key treatment and recovery processes for WEEE?
- How can the PRO's apply these models to develop the efficient use of technologies and improve the treatment and recovery of WEEE?
- How can this information be used to promote ecodesign?

In answering these questions, the research was expected to develop and make available the knowledge on the technologies for end-of-life processing and recovery of the WEEE. It was expected to provide a model that could be used to improve the performance of treatment and recovery of the WEEE considering the technical, economic and environmental aspects, as well as to incentivize the producers in the design of electrical and electric products in view of facilitating reuse, dismantling and recovery.

1.4 Research methodology

In the prosecution of the research objectives a methodology was develop. It focused on extensive field work to characterize the operations, the processing techniques and the technologies used in the end-of-life processing infrastructure for WEEE and subsequently on the development of a global model for the entire infrastructure. Finally a case study was developed to demonstrate the contribution of the model to improve the treatment and recovery of the WEEE in Portugal. Figure 1.3 presents a schematic view of the research methodology.

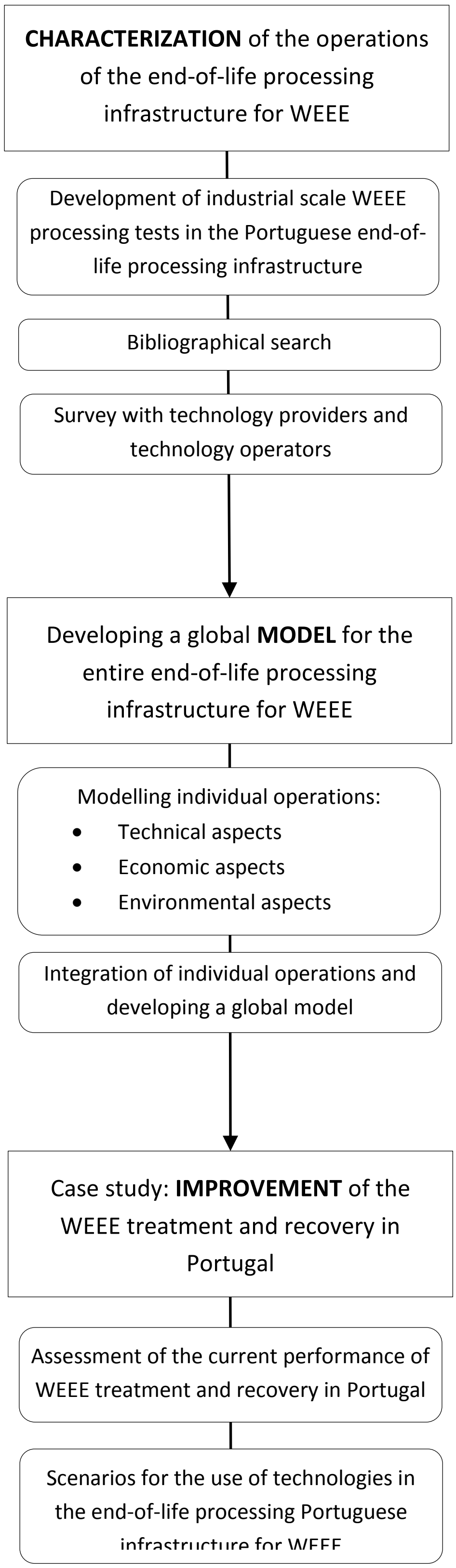


Figure 1.3 – Research methodology

In the first step the characterization of the operations, the processing techniques and the technologies used throughout the entire end-of-life processing chain for WEEE was made addressing the technical, economic and environmental aspects. The characterization involved extensive field work where a broad campaign of industrial scale tests was developed using the Portuguese infrastructure for end-of-life processing of WEEE. The operations and the technologies installed in operators downstream of the Portuguese infrastructure were also characterized based on data from bibliographical sources as well as from a survey done on technology providers and operators. All this work provided comprehensive characterization data on the technologies which had so far been held almost exclusively by the operators. The mapping of the entire WEEE end-of-life processing chain was also an important data.

In the second step a global model was developed for the entire end-of-life processing infrastructure for WEEE. The model incorporated the individual technical, economic and environmental characterization of the operations performed and their coupling to comprise the different alternative technologies used in the end-of-life processing of each of the five categories of WEEE. The model was calibrated using data from the Portuguese infrastructure and the downstream operators.

In order to demonstrate the benefits of the model to improve the performance of the end-of-life processing infrastructure for WEEE, a case study was developed by applying the global model to the Portuguese infrastructure and the respective downstream operators. The third stage of the methodology involved the assessment of the current performance of WEEE treatment and recovery achieved in Portugal by 2012 using the expected amounts of collected WEEE. This constituted the baseline performance level from which it was attempted to improve. Using the results of the global model and the expected amounts of WEEE to be processed between 2012 and 2016, the most efficient use of the end-of-life processing technologies was calculated to see if it could attend a set of improvement goals.

1.5 Thesis outline

The thesis is organized in five chapters, including the present one. Figure 1.4 presents a schematic view of the structure of the thesis, the contents of each chapter and the main contributions.

Structure	Contents	Main contributions
Chapter 1 Introduction	This chapter presents the background and states the problems addressed in the thesis. Specifically, it presents the research questions and objectives and establishes the basic concepts and methods applied in the research work.	
Chapter 2 Experimental Characterization of Industrial End-of-life Processes for WEEE	The present chapter characterizes the industrial processes involved in the treatment and recovery of the WEEE. It includes the experimental methodology that was developed and implemented to characterize the end-of-life processing of WEEE applied in the Portuguese infrastructure. It also includes the characterization of the downstream processes done based on bibliographical search and survey with operators and providers of end-of-life technologies for WEEE.	Methodology to collect data on the technical, economic and environmental aspects of the end-of-life processing of the WEEE.
Chapter 3 Developing a model of the end-of-life processing of WEEE	The chapter presents the development of a global model for the end-of-life processing of WEEE. It describes how the operations were modelled based on the data that was made available from extensive field work and other information sources. It describes the modelling of the technical, economic and environmental aspects characteristic of the operations and how these are coupled to model the various types of technologies used to treat and recover the WEEE. The global model is calibrated using the Portuguese infrastructure.	Calibrated global model of the infrastructure for the end-of-life processing of WEEE, including models of the alternative end-of-life technologies used to treat and recover the WEEE and the respective technical, economic and environmental aspects.
Chapter 4 Case study: improving the WEEE treatment and recovery in Portugal	The chapter presents the assessment of current performance of the Portuguese infrastructure for the treatment and recovery of the WEEE. It describes and presents the improvement of the performance, considering the technical, economic and environmental aspects.	Efficient use of end-of-life technologies and improve the performance of the treatment and recovery of WEEE considering the technical, economic and environmental aspects.
Chapter 5 Conclusions and recommendations	The chapter presents the conclusions from the research, identifies the key contributions and suggests possible areas of future work.	

Figure 1.4 – Thesis outline

2 Experimental characterization of industrial end-of-life processes for WEEE

The first step of the research work characterized the industrial processes applied in the end-of-life processing of WEEE. This constituted the basis for the development of models for the operations performed and a global model for the entire end-of-life processing infrastructure for WEEE considering the technical, economic and environmental aspects.

2.1 End-of-life processing technologies for WEEE

According with the technical and economic constraints of managing end-of-life electrical and electronic equipment, the take back schemes sort and process WEEE in five distinct categories, based on similar physical characteristics of the discarded equipment which enable them to be processed together. Table 2.1 presents examples of equipment in each treatment category and their main characteristics.

Table 2.1 – WEEE treatment categories

Treatment categories	Main contents (non-exhaustive)	Main characteristics
Large household appliances (A)	Includes the so-called white goods, such as washing machines, tumble dryers, dishwashers, microwave ovens, stoves, etc.. Does not include cooling and freezing appliances.	Dominated by metal content. It is classified using the European Waste List (EWL) as non-hazardous waste.
Cooling and freezing appliances (B)	Includes refrigerators and freezers that contain refrigerant substances, such as CFC's and HCFC's (ozone layer depleting substances) and pentane (non-ozone layer depleting substances).	Dominated by metal content. The presence of ozone depleting substances requires proper handling to avoid any release of those substances during collection, transport and processing. It is classified using the EWL as hazardous waste.
Small domestic appliances (C)	Includes consumer electronics (e.g. digital cameras, audio equipment, DVD players), information technology and communication equipment (e.g. personal computers, mobile phones, printers) and small household appliances (e.g. small vacuum cleaners, toasters, coffee machines). Often it contains smaller equipment from category large household appliances, such as microwave ovens.	Dominated by metal and plastic content. High levels of rare and high value metals (e.g. platinum, gold, silver). It is classified using the EWL as non-hazardous waste.
Gas discharge lamps (D)	Includes straight fluorescent tubes and compact fluorescent bulbs.	Glass dominated products, with presence of mercury that requires special processing to be removed. It is classified using the EWL as hazardous waste.
CRT televisions and monitors (E)	Includes televisions and monitors with cathode ray tubes display technology.	Glass dominated products, with the presence of leaded glass and fluorescent coating substances that both require special handling to be segregated. It is classified using the EWL as hazardous waste.

In general, waste electrical and electronic equipment are processed using technologies that are made up of a combination of manual dismantling and mechanical operations, such as shredding and separation of material fractions.

In the context of Directive 2002/96/EC, the selection of technologies and their use in processing the WEEE has two main objectives:

- Ensure the legally mandatory *de-pollution stage* with the selective treatment of hazardous substances and components (as required in the Annex II of the WEEE Directive);
- Achieve the legally mandatory WEEE reuse/recycling targets as well as the recovery targets.

From the operator's point of view, the selection of technologies has to consider the efficiency and effectiveness of the *de-pollution stage*, as well as the *additional processing* of the WEEE which will enable to recover its economic value, by selling the material fractions to subsequent end-of-life processing operators, while minimizing the amount of non-recyclable material, which normally bares a cost associated.

If the *de-pollution stage* is critical to ensure the mandatory removal of hazardous substances and components from WEEE, the *additional processing* is determining to maximize the rate of reuse, recycling and recovery and to minimize the disposal.

In general, the dismantling, shredding and separation of WEEE enables the recycling of the metal content and part of the other material fractions, such as plastics, glass, or wood. For other material fractions whose recovery is not possible because of technical or economic reasons, there are three options left: incineration with energy recovery, applicable for fractions with high energy content (e.g. rubber, textiles) and usually not contaminated with hazardous substances; deposition in landfill, for material fractions with low energy content; and incineration or thermal destruction for material fractions with hazardous substances that require this kind of destruction.

In the following sub-sections, the main technologies for processing WEEE of each of the five treatment categories are characterized. The technologies are representative of those used in the end-of-life processing chain in most European countries, including Portugal.

2.1.1 Large household appliances

Large household appliances (A) include WEEE of large dimensions, such as washing machines, dishwashers, stoves, microwave ovens, tumble dryers, among other, and do not include cooling and freezing appliances.

The processing of large household appliances is done by an initial manual dismantling, where mandatory removal of substances and components is ensured (e.g. removal of capacitors), followed by shredding of the carcass and the automatic separation of metals and other materials using magnetic and non-ferrous metals separators.

The waste electrical and electronic equipment from treatment category A are processed in Portugal by waste management operators of both large and small scale. The most typical are:

- Large scale car shredders, that use high capacity shredding and automatic separation technologies, and
- Smaller scale operators, that apply manual dismantling and sometimes small capacity shredding and separation technologies.

In both cases the mandatory selective treatment is done, which essentially implicates the use of manual dismantling operations to remover hazardous substances and components. Table 2.2 presents the main hazardous substances and components removed separately from large household appliances (legally mandatory according with requirements from Annex II of Directive 2002/96/EC).

Table 2.2 – Main hazardous substances and components removed from large household appliances (required in Annex II of Directive 2002/96/EC)

Treatment category	Main hazardous substances and components removed
Large household appliances (A)	• External electric cables • Capacitors • Printed circuit boards • Oil • Asbestos containing waste • Components containing refractory ceramic fibres • Mercury containing components

After the *de-pollution stage*, the additional processing can present two different approaches: in the case of large scale car shredders, WEEE are processed in the car shredder and separator, resulting material fractions that can be dispatched to final acceptors to be recovered and/or eliminated; in the case of smaller scale operators, the WEEE are processed by manual dismantling to separate material fractions. Part of these can be sent to final acceptors, and the remainder has to be sent to further processing, by large scale operators and/or by specialized operators which hold the necessary final processing technologies. Figure 2.1 shows the typical diagram of operations for processing of large household appliances.

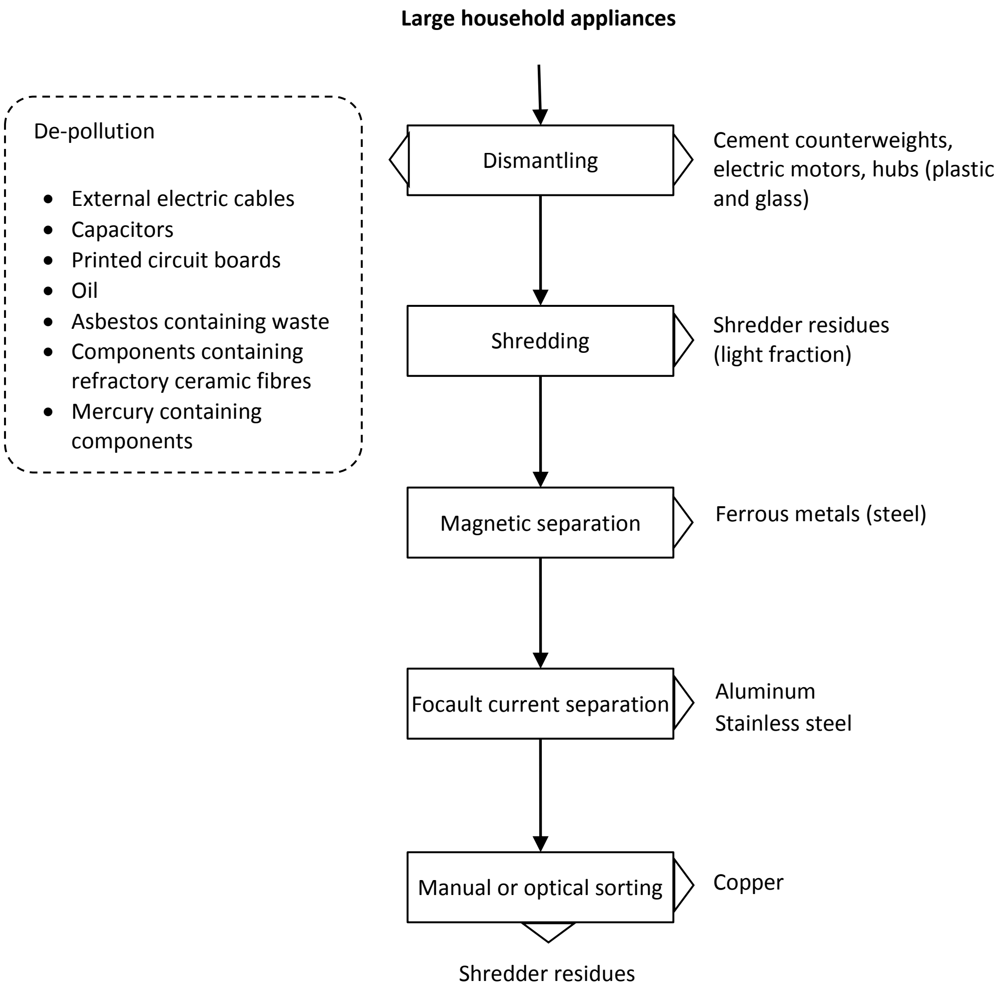


Figure 2.1 – Processing stages of large household appliances (based on technologies installed by operators in the Portuguese infrastructure)

2.1.2 Cooling and freezing appliances

Cooling and freezing appliances (treatment category B) include refrigerators, freezers, food and drink dispensers and air conditioning equipment. These have similar material content to large household appliances, but they also contain refrigerant fluids used in the cooling systems (e.g. mostly CFC's and halon) that present a threat to the ozone layer if released in to the atmosphere.

The refrigerant fluids are also present in the insulating materials that make part of the inner structure of the walls of cooling and freezing appliances, and in case they're put in contact with the atmosphere there is release the refrigerant fluids contained in them.

The presence of substances with ozone layer depletion potential in cooling and freezing appliances implies that such equipment have to be processed in close chamber systems, ensuring the extraction and further collection of the refrigerant substances, preventing their release to the atmosphere.

Additionally, cooling and freezing appliances contain other hazardous substances and components that have to be removed separately, in order to avoid contamination of the resulting material fractions from processing equipment of treatment category B. Table 2.3 presents the list hazardous substances and components removed separately during the processing (legally mandatory according with requirements from Annex II of Directive 2002/96/EC).

Table 2.3 – Main hazardous substances and components removed from cooling and freezing appliances (required in Annex II of Directive 2002/96/EC)

Treatment category	Main hazardous substances and components removed
Cooling and freezing appliances (B)	• External electric cables • CFC, HCFC, HFC and HC • Lamps • Oil • Capacitors

Although refrigerant substances with ozone layer depletion potential are no longer used in new cooling and freezing appliances, following the phasing out determined in the Montreal Protocol, the fact remains that old equipment still contain CFC's and halon and as they reach the end-of-life they have to be processed adequately to ensure the capture of such substances.

A side effect of the phasing out was the use of substitute refrigerants, containing pentane, which now present and additional challenge, as the excess concentration of these during processing at the end-of-life may result in fires and explosions. Consequently, processors of cooling and freezing appliances now use nitrogen to remove oxygen from the close chamber systems, and reduce the risk of fire and explosions in case of heavy concentration of pentane based refrigerants.

The processing of cooling and freezing appliances is directed to the removal and capture of hazardous substances, including the refrigerants with ozone layer depletion potential, and the recovery of the metal containing fractions. Figure 2.2 shows the subsequent steps involved in processing of cooling and freezing appliances.

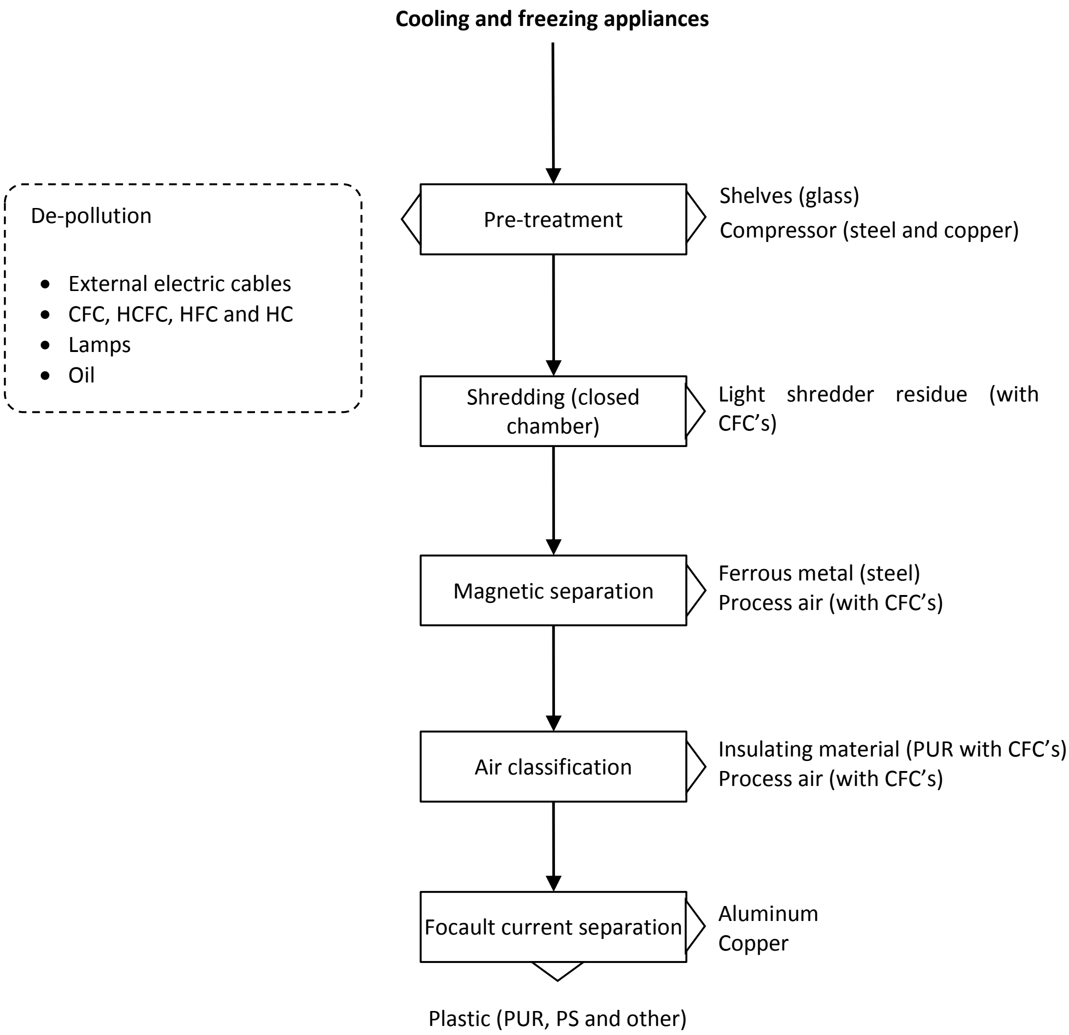


Figure 2.2 – Processing stages of cooling and freezing appliances (based on technologies installed by operators in the Portuguese infrastructure)

The first stage is designated by pre-treatment, and includes manual dismantling of components (e.g. generally external cable, lamps and removable objects on the inside of equipment, like glass shelves and plastic drawers, as well as any waste food leftovers) followed by the removal of fluids from the cooling system, which is done by piercing the compressor or any tubing with a specialized tool that is attached to a vacuum extraction system. The fluids containing oil and refrigerants together are processed in a specific separator, where the gas and oil are separated. The oil is processed to be further degassed using one of the following technologies, increased temperature, nitrogen injection, or ultra-sound. The refrigerants are stored in a tank and then sent to be destroyed by thermal destruction.

After removal of fluids, the compressors are cut off from the cooling and freezing equipment and stored. The compressors contain ferrous metals and copper, and generally are sold to other processors that recycle their material content.

The remaining carcass of the equipment is shredded in the next stage of processing. This is done using a shredder in a close chamber, filled with a high concentration of nitrogen. The following steps are intended to separate the different materials, namely ferrous and non ferrous metals, plastics and the insulating material which also contains refrigerants, in order to ensure their recovery or adequate disposal.

2.1.3 Small domestic appliances

Small domestic appliances (treatment category C) is a very heterogeneous waste flow and it includes a wide variety of equipment, like toys, electric tools, information technologies, audio and telecommunication equipment, consumer equipment and other domestic appliances of small size.

In general, equipment from treatment category C present a broad spectrum of materials and components, some of which are hazardous and have to be removed separately (e.g. printed circuit boards, batteries, ink lints and toner cartridges, liquid crystal displays). In Table 2.4 the main components to be removed separately from Small domestic appliances are listed. The removal is legally mandatory according with requirements in the Directive 2002/96/EC.

Table 2.4 – Main hazardous substances and components removed from small domestic appliances (required in Annex II of Directive 2002/96/EC)

Treatment category	Main hazardous substances and components removed
Small domestic appliances (C)	• External electric cables • Printed circuit boards • Capacitors • Batteries and accumulators • Toner cartridges • Ink lints • Lamps • Liquid crystal displays

Given the variety of components and materials in Small domestic appliances, the processing is equally varied, being done with the use of different technologies. The most common technology is based on manual dismantling of equipment, to remove hazardous components and substances, as well as to separate material fractions for recovery, such as ferrous metals, non ferrous metals and plastics.

Manual dismantling is generally less destructive than mechanical processing, especially shredding, and this can be an advantage when the intention is to separate whole components for reuse or to avoid release of hazardous substances contained in specific components, such as ink in ink lints. However, manual dismantling generally has a small capacity and a high cost, and

consequently processing of Small domestic appliances is done in a combination of manual dismantling and mechanical processing.

Figure 2.3 presents the diagram for contemporary processing of equipment from treatment category C, using a combination of manual dismantling and mechanical processing.

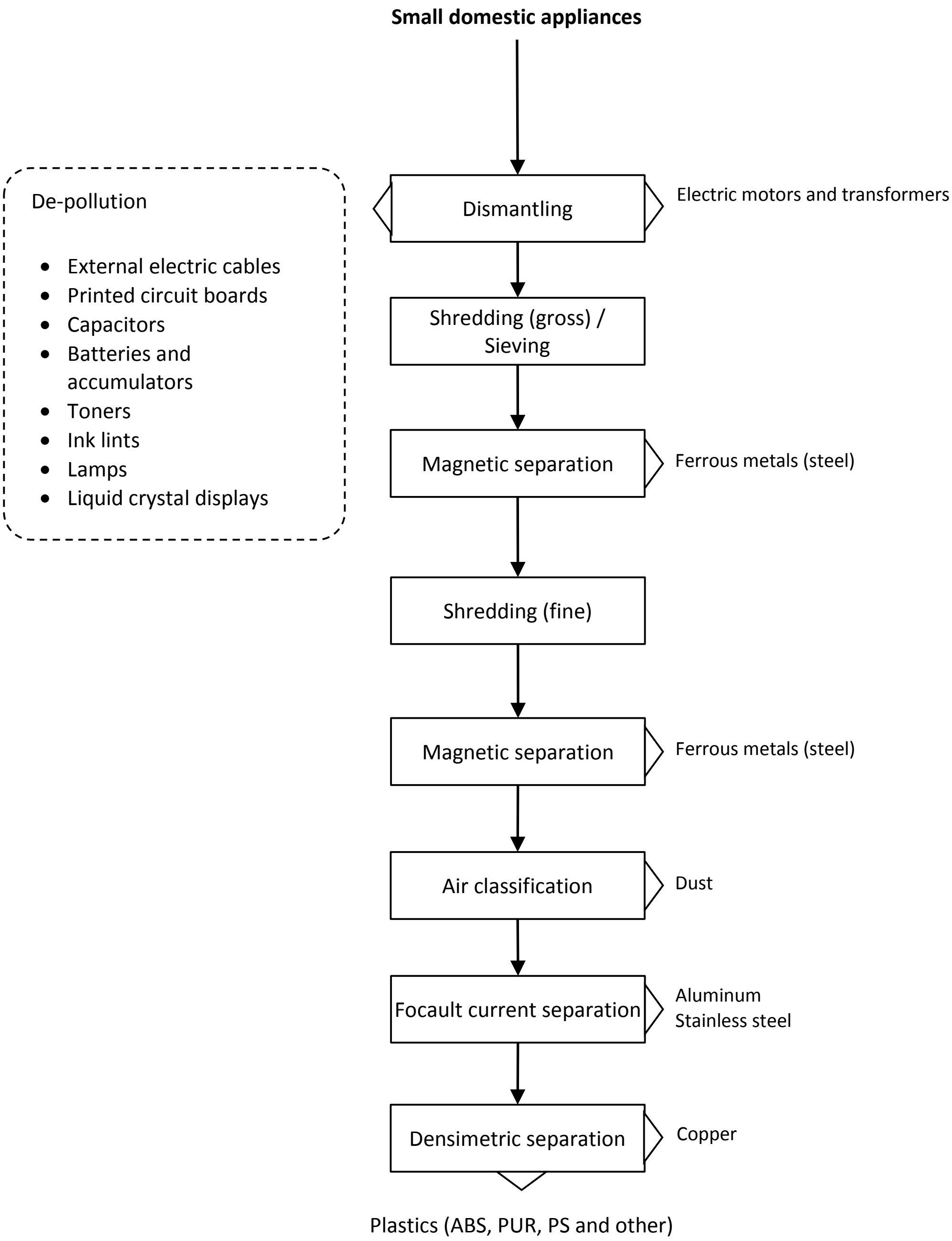


Figure 2.3 – Processing stages of small domestic appliances (based on technologies installed by operators in the Portuguese infrastructure)

2.1.4 Gas discharge lamps

Treatment category D includes all gas discharge lamps, from straight fluorescent tubes to the newer energy efficient compact gas discharge lamps. Filament lights are not included in the treatment category or the scope of the WEEE Directive.

Gas discharge lamps are a treatment category because of the mercury present in them, which has a significant impact on human health, at the nervous system level. Their separate removal is legally mandatory as gas discharge lamps are listed in Annex II of Directive 2002/96/EC.

Additionally, processing of treatment category D enables the separation of glass, the main material in lamps' composition, as well as non ferrous metals and phosphorous powders. Although phosphorous powders represent a small percentage of the lamp's weight, it holds the mercury content. This requires further processing of the contaminated powders to ensure the separation of the mercury. Phosphorous powders have been discovered to include rare earth elements, and very recently its use as a source of such elements has been a driver of research and development in Europe.

In Figure 2.4 the processing of Gas discharge lamps is presented in a schematic form. The lamps are fed on to a shredder, fitted with air extraction system. After shredding a series of operations take place to separate the ferrous metals, non ferrous metals and glass. Finally, the phosphorous powders that were collected are processed in batches in a distillation, to remove the mercury content from them.

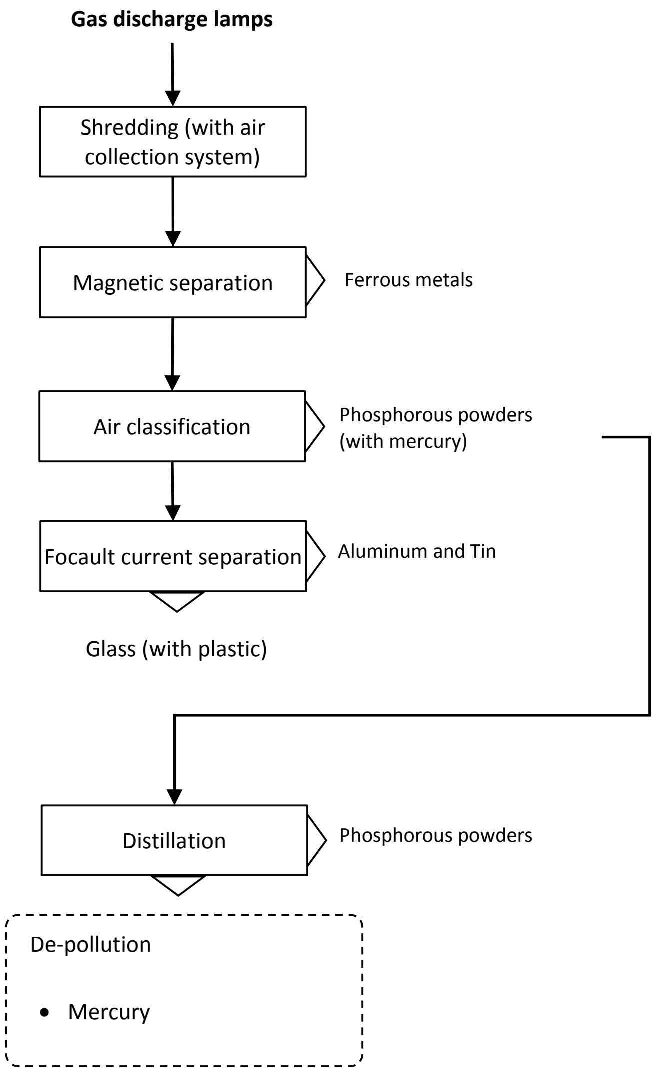


Figure 2.4 – Processing stages of gas discharge lamps (based on technologies installed by operators in the Portuguese infrastructure)

2.1.5 CRT televisions and monitors

Treatment category E includes television sets and monitors with cathode ray tube technology. CRT technology is being discontinued, and replaced with modern display technologies such as plasma and liquid crystal display (LCD). However, given the average lifetime of CRT televisions and monitors it is expected that such equipment will continue to become waste in significant amounts for a long time.

CRT's have to be removed separately from monitors and televisions, because they contain leaded glass, as well as phosphorous elements that are classified as hazardous. Other hazardous components and substances also have to be removed separately according with requirements from Directive 2002/96/EC. Table 2.5 lists the main hazardous components and substances to be removed from equipment of treatment category E.

Table 2.5 – Main hazardous substances and components removed from CRT televisions and monitors (required in Annex II of Directive 2002/96/EC)

Treatment category	Main hazardous substances and components removed
CRT televisions and monitors (E)	• Leaded glass • Phosphorous powders • External electric cables • Printed circuit boards • Capacitors • Plastics with Brominated flame retardants

The additional processing done to CRT televisions and monitors is intended mostly to separate and recover the glass, metals and plastic content. The CRT televisions and monitors are initially subjected to manual dismantling, where they are stripped of the external electric cable and of the external wood or plastic casing. This is done to gain access to the CRT inside the equipment and is presently the only form that can do so and preserve the integrity of the CRT, which is essential for the next stage in processing. In the course of the manual dismantling, several components and materials are separated from the equipment, including power supply units, printed circuit boards, plastic, wood and other.

The processing of CRT's requires special care to avoid the loss of leaded glass into other material fractions, which will contaminate them, and the uncontrolled release of the hazardous phosphorous powders from the inside face of the screen. The CRT is cut in to two halves, which enables the separation of the tube leaded glass from the screen glass. Afterwards, the screen is vacuumed to remove the layer of phosphorous powders.

In order to maximize the recovery of materials from CRT, one critical aspect is to ensure the proper separation of the tube glass and to promote its recovery. Until recently, this lead containing glass was used to produce new CRT's. Eventually, with the decay of CRT production from its substitution by other display technologies, the recovery of leaded glass has proved a difficult challenge and is currently the focus of research to find new applications, most of them in the production of ceramic materials and abrasion specific materials (after extraction of the lead content via chemical processing) or as slag building agent in lead foundries.

The material fractions such as ferrous and non ferrous metals, and plastics, are recycled and/or incinerated with energy recovery. Here also, the recycling of plastics containing brominated flame retardants is a challenge, because the use of such flame retardants on new products is presently banned.

Figure 2.5 presents the schematic view of end-of-life processing of CRT televisions and monitors, according with state of the art processing technologies installed in Portuguese operators.

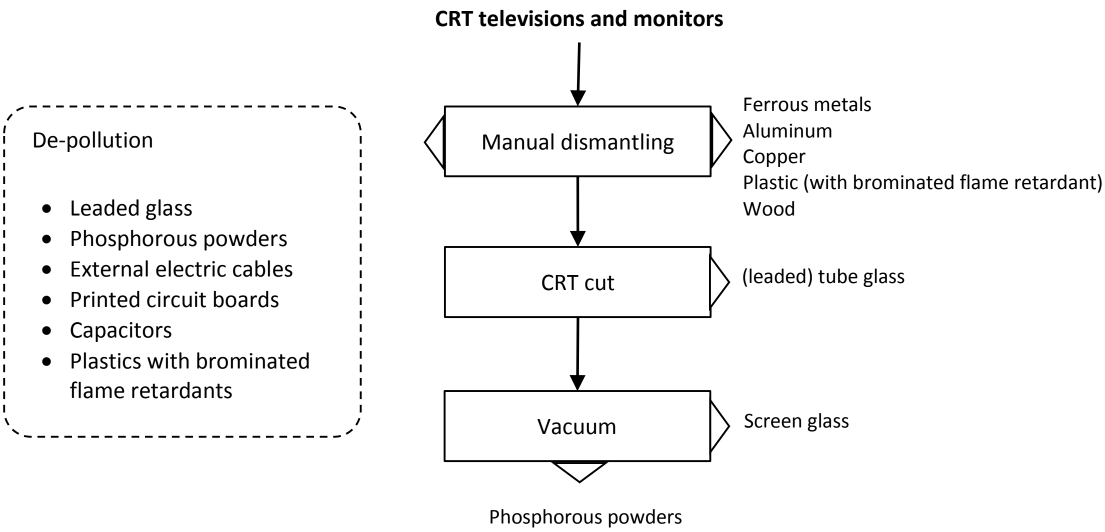


Figure 2.5 – Processing stages of CRT televisions and monitors (based on technologies installed by operators in the Portuguese infrastructure)

2.1.6 Emerging WEEE flows

The continuous development of new electrical and electronics products also poses new challenges to the recycling industry. The main challenges come from equipment such as liquid crystal displays and also from photovoltaic panels.

The volumes of discarded LCD equipment are rising although only expected to reach the current volumes of CRT by 2030 (Grieger, 2010). There isn't yet a consolidated processing technology that ensures the efficient and effective de-pollution and recovery of the LCD equipment, in particular the safe and integral removal of the backlights in the equipment that contain mercury. There have been some documented experiments of dismantling these equipment (SWICO Recycling, 2011), which so far proved to be the only process technically able to deal with issue of the backlight removal without breakage; nevertheless it is yet to prove economically sustainable. As a consequence, most LCD televisions and monitors that currently reach the end-of-life are either stored by the waste management operators or discarded in landfills or incinerators (United Nations University, 2007) which are not the most appropriate destinations for WEEE.

Regarding photovoltaic panels, these just became part of the scope of the WEEE Recast and so WEEE take back systems will have to prepare to collect, treat and recover such equipment. However, the long average use lifetime of more than 20 years means that the occurrence of waste volumes from such equipment is still some years ahead in the future, expected to become significant by 2035 (Bio Intelligence Service, 2011). Presently, only a very small number of companies in Europe have systems to collect and recover photovoltaic panels. Such companies operate technologies to process the discarded photovoltaic panels, mostly intended to promote the reuse of the solar cells (Bio Intelligence Service, 2011).

Over the next decade at least, it is expected that these emerging WEEE flows will not be significant in respect to the overall volumes of WEEE. In parallel, the end-of-life technologies to process these waste flows are still in the early stages of development. In this context, the emerging WEEE flows and their processing technologies have not been considered in the analysis of the present thesis.

2.2 The Portuguese infrastructure for processing of WEEE

In the context of the research objectives, it was fundamental to execute experimental field work to characterize the operations of the end-of-life processing technologies in the respective technical, economic and environmental aspects. This was critical to develop and make available the knowledge and provide the input data for the global model that was developed. The Portuguese infrastructure constituted a solid option to develop the experimental analysis and collect field data on the technologies used in end-of-life processing of WEEE.

In Portugal, the waste management sector in general and the WEEE processing in particular have had significant developments over the last decade, with the creation of new operators which have implemented state of the art technologies to process the WEEE. With the transposition of the WEEE Directive to the Portuguese legal framework in 2004, the responsibility of producers on the end-of-life management of the products they place on the market was set. By then, there were only two operators working in Portugal that had the technologies and personnel required to process WEEE according with legal requirements: one was fully dedicated to the processing of lamps and the other one dedicated to processing large household appliances, cooling and freezing appliances, small domestic appliances and CRT televisions and monitors.

The development of the WEEE take-back schemes by AMB3E and ERP Portugal followed in 2006 and helped to create the conditions for new investments and the development of an infrastructure for the end-of-life processing of the WEEE in Portugal. The PRO's developed a network of operational partners, by signing contracts with operators that provided capacity for processing WEEE according with the requirements of the WEEE Directive, including the removal of hazardous substances and components as well as the achievement of minimum reuse/recycling and recovery targets. The network of partners included operators in the entire country, including the continental and the island territories (Azores and Madeira) of Portugal.

With the mandatory legal requirements concerning the selective treatment and the recovery of WEEE, and having PRO's mandated and capable to provide financial assistance for the necessary WEEE processing activities, a number of waste management companies started to look in to WEEE as one viable business opportunity. Since 2006, various new operators were created in Portugal and others that already existed also decided to invest in WEEE processing technologies. By 2012 a total of 20 operators were operating under the WEEE take back systems managed by AMB3E and ERP Portugal, as Figure 2.6 shows.

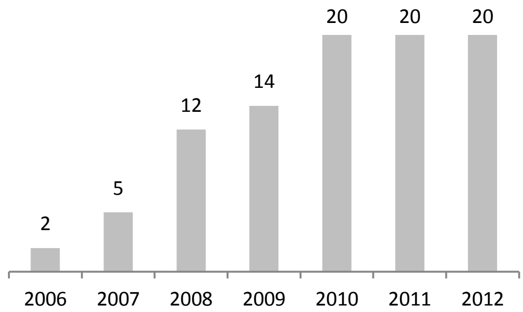


Figure 2.6 – Evolution of the number of WEEE processing operators in the Portuguese infrastructure (AMB3E, 2012 and ERP Portugal, 2010)

WEEE processing operators in Portugal can be grouped into two generic types, considering their distinct sizes and levels of technological development:

- Large scale operators: these incorporate state of art technologies, including mechanical shredding and automatic separation equipment, combined with manual dismantling processes. The material fractions obtained from processing are generally sent to final acceptors to be reused, recycled, energy recovered and/or disposed.
- Small scale operators: these base their operations on manual dismantling processes, both for de-*pollution stage* and the *additional processing*. An important part of the material fractions obtained by these operators are sent to large scale or other small scale operators for further processing and only a small part can be sent directly to final acceptors, for reuse, recycling, energy recovery and/or disposal.

Figure 2.7 presents a simplified diagram with both types of WEEE processing operators.

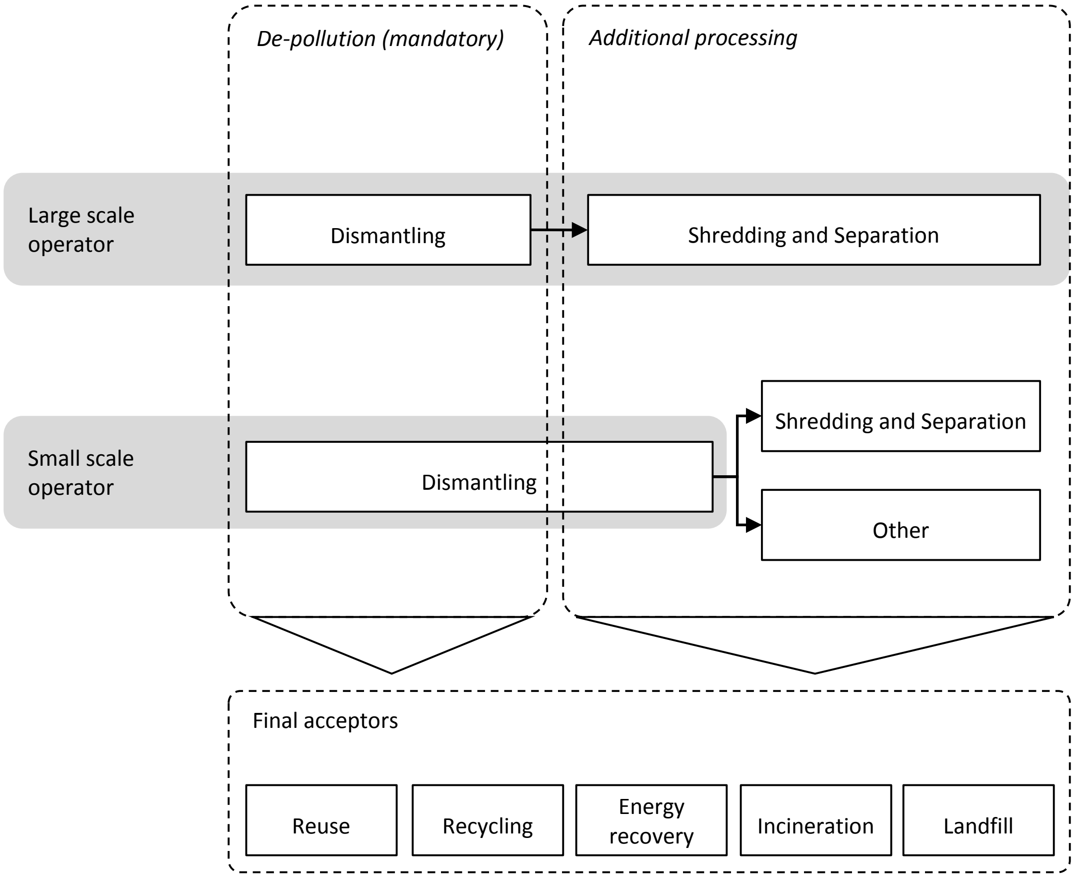


Figure 2.7 – Generic types of WEEE processing operators (based on technologies installed in the Portuguese infrastructure)

Apart from the size, not all WEEE processing operators in Portugal are able to process the WEEE from all five treatment categories. The majority of them process WEEE from treatment categories A and C, respectively large household appliances and small domestic appliances, which are classified as non-hazardous WEEE and have processing requirements that can be fulfilled with less complex technologies. On the other hand, the processing of WEEE from treatment categories B, D and E, respectively cooling and freezing appliances, gas discharge lamps and CRT televisions and monitors are classified as hazardous WEEE and are processed by a stricter group of operators.

From a geographical perspective, the operators in the island territories of Azores and Madeira are capable to process WEEE of treatment categories A and C. All the capacity in the Portuguese infrastructure for processing WEEE of treatment categories B, D and E is installed in operators located in the continental territory of Portugal. Figure 2.8 shows the localization of the WEEE processing operators in the Portuguese infrastructure.

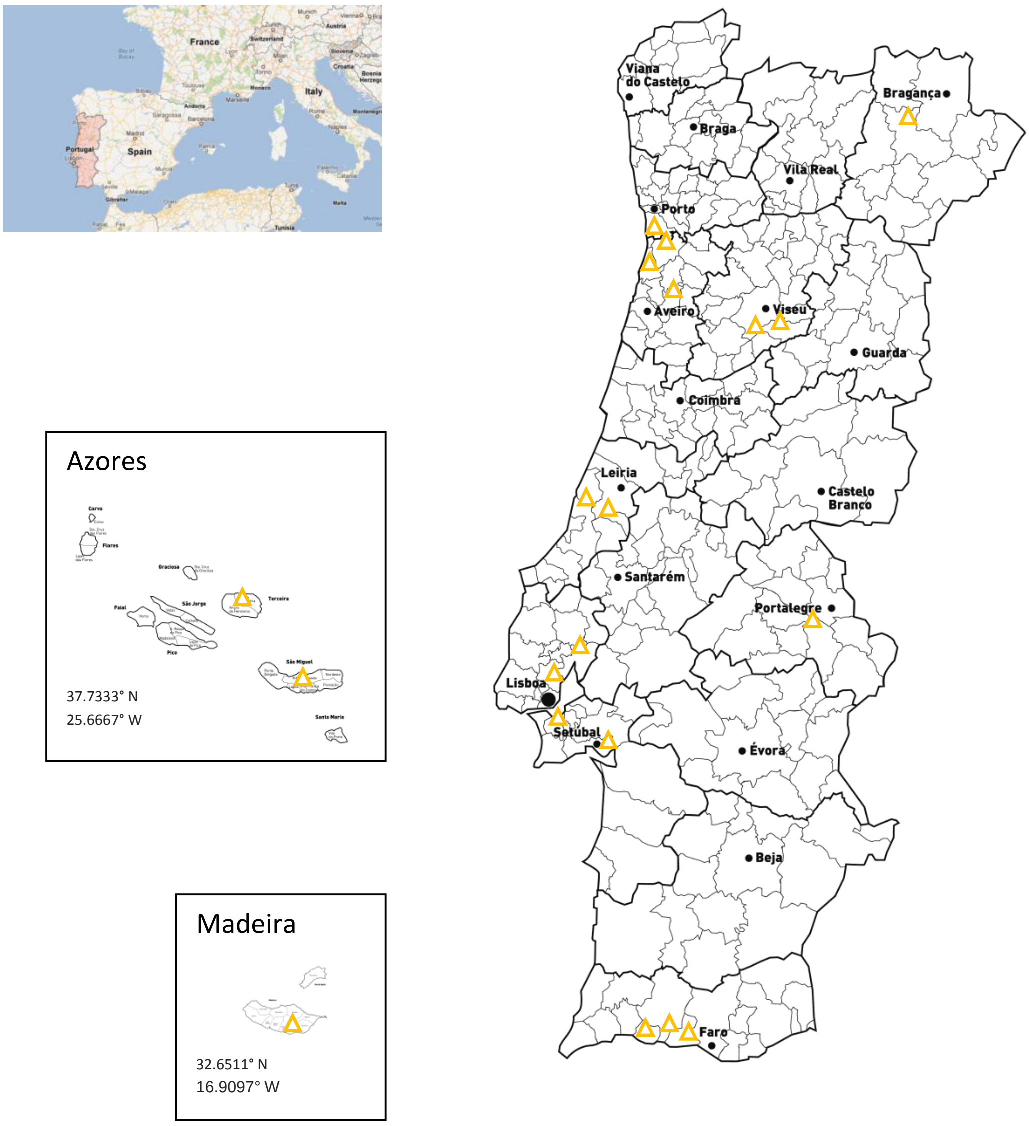


Figure 2.8 – Location of the facilities of the WEEE processing operators in the Portuguese infrastructure

The processing capacity (amount of WEEE that can be processed in a given period of time) is a critical characteristic of the technology of each WEEE processing operator and ultimately of the entire infrastructure of WEEE processing. The respective data was obtained for each individual processing operator in the Portuguese infrastructure. For confidentiality reasons the data is not disclosed.

In brief, there are a total of 19 operators able to process large household appliances in the Portuguese infrastructure. The top 10 operators represent approximately 80% of the total processing capacity of the infrastructure for treatment category A.

Regarding Cooling and freezing appliances, there are 3 operators in the Portuguese infrastructure capable to process such WEEE and they have similar processing capacities.

Regarding the processing of Small domestic appliances, there are 18 in total in the Portuguese infrastructure and the top 8 operators represent more than 80% of the total processing capacity.

Only 2 operators in the Portuguese infrastructure are capable to process Gas discharge lamps and have distinct processing capacities.

Finally, regarding CRT televisions and monitors, 3 operators are capable to process such WEEE, and the top 2 represent approximately 80% of the total installed capacity.

2.3 Objectives and methodology of end-of-life processing tests for WEEE

An end-of-life processing test for WEEE refers to an experimental procedure where WEEE of a pre-selected type is processed for a minimum amount or during a minimum period of activity. The test was intended to collect the following data:

- Diagrams of the operations that constitute the end-of-life technology;
- Individual amounts of the input and the different outputs for each operation;
- Material composition of the input and of the output fractions obtained;
- Effective processing capacity (throughput);
- Identification of the downstream operators and the types of subsequent operations for each of the fractions obtained.

The methodology for the end-of-life processing tests was developed consisting of three phases: planning and preparation, processing of the pre-selected WEEE and data compiling, and the assessment of results. Figure 2.9 presents a schematic view of the methodology.

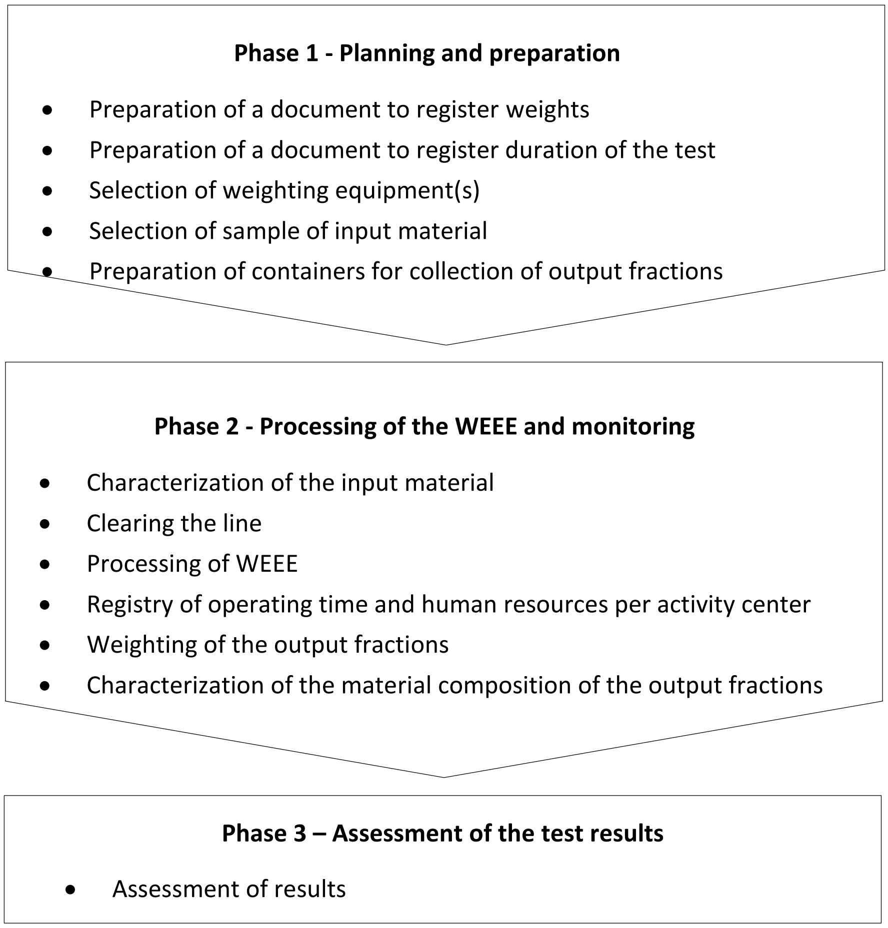


Figure 2.9 – Methodology for end-of-life processing tests for WEEE

Based on the methodology, a protocol was developed describing the activities and resources necessary to execute an end-of-life processing test.

The tests were developed by the researcher, including the scientific coordination and the operational execution. With the close collaboration of the PRO AMB3E and the operators in its network, it was possible to develop a broad and representative campaign of tests to characterize the Portuguese infrastructure.

In the following sub-sections the methodology and execution of the end-of-life processing tests for WEEE are described step by step.

2.3.1 Phase 1 - Planning and Preparation

The execution of any end-of-life processing test required initial planning and preparation. At this stage, the people involved in the test including the researcher and representatives from the operator and the PRO exchanged information to agree on the scope and date for the execution of the test, or the tests in case there was more than one. As general approach, a single initial WEEE processing test would be arranged and prepared for every operator. This was crucial to

gain the trust of the operator and had the advantage of avoiding excessive preparations by the operator, which might jeopardize the reality of the results. After the initial test was completed and all the results were discussed, the researcher and the representatives from the PRO and the operator would sit down again and arrange for the next tests. During the planning and preparation of each test, agreement had to be reached on the following items:

- Date for the start of the test;
- Type of input material for the test (e.g. WEEE of a specific treatment category, such as 'Large household appliances');
- Minimum amount of input material to be treated in the test or minimum period of activity to be tested;

Regarding the dates for the start of the WEEE processing tests, the beginning or the middle of the week would be preferable and the end of the week would be avoided, especially if that meant that there was an interruption during the weekend. All these aspects were taken in consideration when planning and preparing for the test in order to minimize any factors that could affect the representativeness of the results in the end.

The type of input material was set per treatment category of WEEE. In this context, the WEEE processing tests were done for five different types of input material respective of each of the five WEEE treatment categories:

- Large household appliances (treatment category A)
- Cooling and freezing appliances (treatment category B)
- Small domestic appliances (treatment category C)
- Gas discharge lamps (treatment category D)
- CRT televisions and monitors (treatment category E)

Each WEEE treatment category incorporates different types of electrical and electronic equipment. In general, the inflow of material to a processing operator will be characteristic of its origin: if it comes from domestic or professional activities and from urban or rural populations. On average, for a given operator the inflow of material does not vary significantly. The intention was that the tests could be executed in a consistent form throughout the various tests.

Regarding the sample of input material, the fundamental requirement was that it would be representative of the average inflow of WEEE processed. Each operator was responsible for the selection of the sample of input material and then it had to be checked and approved by the researcher and the representative from the PRO before the WEEE processing test could begin.

The minimum amounts of input material and minimum duration of the test are interdependent variables, considering the processing capacity. In this context, either one could be used to set the requirements of the WEEE processing test. In general, a minimum amount of WEEE to be processed would be set according with the values defined in the standards for mass balance accounting developed by the WEEE Forum (WEEE Forum, 2008b). The minimum amount should provide between 2 straight working days and 1 week of standard processing activity including preventive maintenance or any other activities that the operator would normally do. In cases

where abnormal occurrences took place during the test that would affect its duration significantly (e.g. failure of processing equipment) then the minimum amounts of input material could be adjusted.

The researcher was physically present in the facilities throughout the duration of the WEEE processing tests, making sure that the protocol was being followed and the results could be validated in the end. Table 2.6 presents the minimum amounts of input material and the minimum duration of the WEEE processing tests per category of WEEE achieved during the campaign.

Table 2.6 – Minimum amounts of input material and duration of the WEEE processing tests

	Minimum input material per test (kg)	Minimum duration per test (working days)
Large household appliances (A)	6876	2
Cooling and freezing appliances (B)	17420	3
Small domestic appliances (C)	6094	3
Gas discharge lamps (D)	3150	3
CRT televisions and monitors (E)	3162	2

Before the start of the WEEE processing test, each operator provided the following data:

- Confirmation of the type of input material, the minimum amount of WEEE or period of activity to be tested and the date for the start of the test;
- Expected date for the completion of the test;
- WEEE processing diagram, including the operations and the respective fractions that would be obtained;
- List of final fractions to be obtained with the respective indication of the disposal and/or recovery operations as well as the subsequent destinations.

In general, the diagram of operations and the list of final fractions with the respective destinations were updated during the execution of the test, as a result of the observation *in-loco* of the processing equipment being used and discussions with the people responsible for the operators.

Once the basic conditions were established by the parties, it was the operator's responsibility to prepare for the execution of the WEEE processing test by taking care of the aspects that follow.

2.3.1.1 Preparation of a document to register weights

The WEEE processing operator had to develop a document to register all the weights of successive weighting operations that were done during the test, including:

- Weight of the input material;
- Weight of the containers;
- Weight of the fractions obtained.

Because for most operators the WEEE processing tests were the first of any mass balance procedures that they had ever implemented, a template version was developed of the weight registry document and provided to the operators in most tests. Figure 2.10 presents an example of a weight registry template used during the WEEE processing tests executed in the Portuguese infrastructure.

Weight registry document

Date: _______________ (dd/mm/yy) **Sheet n.º:** ______

Operator: _______________

Input material: _______________

Duration: start date _______________ / end date _______________

Item (input material, output fraction, collection recipient, etc.)	**WEIGHT (kg)** * signal if **GROSS or NET**	**Recipient** (identification of TARE in kg)	**Time** (h:m)	**Weighting equipment** (name or code)	**Person responsible** for weighting operation
...	...	...	...	...	...

Figure 2.10 – Example of a weight registry document

Although simple, this was a vital document considering that for one WEEE processing test there could be as many as 200 weighting operations of different materials and fractions. In this context, all the weighting data had to be registered, including the weight value as well as data on the registry operation itself (e.g. the date and time when it occurred, the weighting scale that was used, as well as the person in charge of the registry). This was of critical need to ensure the traceability of the results, which could be checked at any moment, allowing for the identification of any mistakes that may have occurred in the data collection and registry process. The document was the basis to ensure that all inputs and outputs from the end-of-life processing of the WEEE had been weighted and accounted for.

2.3.1.2 Preparation of a document to register the duration of the test

Another important variable to characterize the operations during the tests was the time of activity when WEEE was effectively being processed. This was key data for the assessment of the effective processing capacity (throughput) achieved during the test.

In order to register the times during which there was activity in the individual stages of processing of the WEEE, the operator had to prepare and develop a specific document. A template version of a time registry document was developed, as presented in Figure 2.11.

Activity time registry document

Activity centre n.º______ (signal)

# Day	Date (dd/mm/yy)	Periods of activity					
		Period 1 (start h:m | Finish h:m)	Period 2 (start h:m | Finish h:m)	Period 3 (start h:m | Finish h:m)	Period 4 (start h:m | Finish h:m)	Period 5 (start h:m | Finish h:m)	Period 6 (start h:m | Finish h:m)
1							
2							
3							
4							
5							

Figure 2.11 – Example of a activity time registry document

With this document the person in charge would register the date, the start and finish times for several individual periods of activity per processing stage (or activity centre), including those performed by human operators and/or machines. This was essential to monitor the effective working times of different activities, either developed in sequential or in parallel modes during the WEEE processing test. It also allowed to register the occurrence of any planned or unplanned events, like resting periods for human operators as well as start-up times or (preventive or reparative) maintenance periods for machines.

The ability to collect detailed data on the times of the different activities was critical to determine the ("bottleneck") process which ultimately determined the throughput of the entire WEEE processing line. This was useful to verify the effective processing capacity achieved by the WEEE processing operator, but also to identify potential problems with the functioning of the processing equipment.

2.3.1.3 Selection of the weighting equipment

Considering that one of the objectives of a test was to determine the mass balance of WEEE processing, including the weight of the input material and of all individual output fractions, the operator had to provide the adequate weighting equipment, ready and in place to be used during the test. The following options were considered to ensure that the adequate number and type of equipment were set up to allow for the weighting operations:

- Large scales to weight, for example, the input material;
- Medium scales to weight, for example, the containers and the output fractions;
- Small scales to weight, for example, output fractions with small amounts and to do mass balance analysis of small samples of material fractions when determining the average material composition.

Figure 2.12 presents examples of weighting equipment of different sizes and capabilities used in the WEEE processing tests.

Figure 2.12 – Examples of weighting equipment used in the WEEE processing tests

The legal conformity of the weighting equipment (EU Council, 1990 and Governo de Portugal, 1993) was checked in order to ensure that the measured weight data was correct.

2.3.1.4 Selection of sample of input material

The execution of each processing test required the availability of input material in the minimum amount and of the specified type. The WEEE to be processed in the test had to be representative of the typical inflow of material to the operator's installations, in terms of discarded equipment that were present in the sample.

The operator was responsible for the separation of the sample of WEEE and its preparation for the day when the test would begin. Because the minimum amounts were significant, the operator had to keep the necessary space to separately store the input material for the test, while ensuring the legal requirements for the storage facility, namely to be rain proof and on impermeable pavement. The WEEE for the test had to be stored separately from any other WEEE and visibly identified as input material for the test. This was crucial to maintain the integrity of the sample during the test and avoid any contamination with other WEEE. Figure 2.13 presents examples of appropriate storage of input material.

Figure 2.13 – Examples of input material in appropriate storage

The input material was assessed before the first day of testing. Whenever possible, the researcher along with the representative of the PRO would help select the sample of WEEE during a preliminary visit to the installations of the operator. This helped to obtain representative samples of input material, preventing for example the presence of foreign materials that would go undetected until the test would be already running (e.g. waste other than WEEE or mixture of WEEE of other types). It also allowed for a preliminary assessment on the number and types of discarded equipment, components and materials that were present in the input material, later be confirmed in detail during the processing stage of the test.

The operator was asked to predetermine the net weight of the selected input material (without any packaging material) register it in the weight registering document and provide this information. This would help ensure that the operator had the input material ready in the amounts established during the preparatory work. For precaution, the operators were advised

to prepare an amount of WEEE at least 10% higher than the one that would be effectively processed in the test.

2.3.1.5 Preparation of containers for collection of the output fractions

All output fractions had to be stored and weighted separately. The operator provided the containers to store each of the fractions to be obtained during the test, considering the number and capacity to store the amount of each individual one. The process of weighting each fraction and emptying of the containers was done during and/or after the completion of the processing of the WEEE. Considering the expected amount to be obtained of each fraction, a bigger container would require less weighting operations during the processing stage, which also involved emptying and/or replacing the container with an empty one.

This was an important issue considering that the weighting operations used potentially scarce resources, including the forklift and the driver to manoeuvre the cargo and operate the scale, the researcher to monitor and register the weighting data, and sometimes one additional operator to help load and unload the cargo or help with the manoeuvring done by the forklift. The forklift and driver, in particular, were constantly working in many different activities throughout the facilities, including not related with the test (e.g. feed input material to working stations, move of other cargo and weighting of other waste).

The containers were identified (e.g. with individual tags, establishing a code or name of the fraction in each container) to ensure that no material from the test would be lost or that foreign material would be inadvertently accounted in the test. Figure 2.14 presents some examples of the enormous variety of containers used to collect output material fractions during the WEEE processing tests.

Figure 2.14 – Examples of containers used to store output material fractions

Prior to any test, the researcher explored and discussed the planning of the container number, size and identification with the operator, in order to have the test run as smooth as possible, trying to minimize any competition for resources with other activities and the risk of mistakes from it. Anyhow, it evolved that the operators gave priority to the test activities.

2.3.2 Phase 2 - Processing of the WEEE and monitoring

After the planning and preparation stage was done, the WEEE processing and monitoring stage could begin. The first issue to consider was the characterization of the input material as described below.

2.3.2.1 Characterization of the input material

In the beginning of the test, it was necessary to characterize the sample of input material to be processed regarding the following aspects:

- Type of equipment that were present;
- Number and amount of equipment of each type.

The characterization of the input material was important because its contents determined the respective outputs and the processing performance. For example, for WEEE of treatment category E (CRT televisions and monitors), televisions and monitors have different components (e.g. televisions usually don't have printed circuit boards that are present in computer monitors) and in general they present different processing capacities. In this context, the characterization of a sample of input material identifying the relative amounts of televisions and monitors was important and later was used to assess the performance of the WEEE processing as a function of the input. Figure 2.15 presents a good example of a sample of input material of WEEE from treatment category E that was sorted in the different types of equipment: televisions and monitors.

Figure 2.15 – Sample of input material of treatment category E that was sorted in televisions and monitors

The characterization of the input material required handling of the waste and often weighting samples of it. If done simultaneously with the processing of WEEE, it could result in disruptions

to the feeding of input material to the processing line, which would affect the performance and ultimately generate unrepresentative data. In order to avoid any implications on the normal processing of WEEE, in general, the characterization of the input material was done some time before processing (e.g. during the selection of the input material). Occasionally, it was done in the first day of testing but always prior to any processing operations. Additionally, the characterization data was double checked when the material was being fed on to the processing line (e.g. counting the number of units per type of WEEE).

2.3.2.2 Clearing the processing line

Before any treatment operations could begin, the processing line was completely cleared of any material that could still be present from previous processing activities. This meant that the working stations and the respective containers had to be emptied and the floor around the working area had to be cleaned, and also the mechanical processes had to run empty for a while, without any feed, in order to ensure that no material from previous activities would be present and affect the test results. Figure 2.16 presents an example of material that was still left in the processing line from the previous period of activity and was removed before the start of the processing test.

Figure 2.16 – Material removal to clear the processing line

Usually, the WEEE processing operator would do this by the end of the last shift before the test.

2.3.2.3 Processing the WEEE

During this stage, the operator would do its normal operational practice: WEEE would be inputted to the initial operation and it would start being processed. With time the output material fractions would be obtained and collected in individual and identified recipients, which whenever got full were weighted. The processing only finished when the entire designated amount of the input material was processed (or the minimum period of activity was reached) and the total output fractions were obtained. In the end, the processing line would be cleared of all material that could remain, weighted and accounted for in the mass balance.

Figure 2.17 presents a simple schematic view of WEEE processing line, including a series of operations from which output material fractions are obtained.

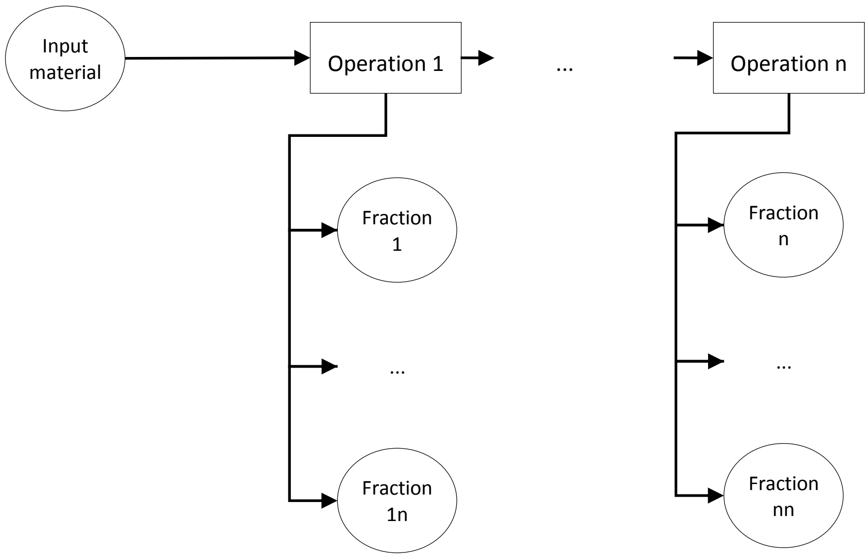


Figure 2.17 – Schematic view of WEEE processing

During the test, the processing had to be representative of the normal operational activity performed by the operator. The researcher was present throughout the duration of the WEEE processing test and observed all the activities (see Figure 2.18). This allowed the characterization of the operational practices while they occurred and if any unplanned event took place it was immediately addressed and the potential impacts on the test results were minimized. In general, the issue was discussed with the person responsible from the operator and action was taken shortly after.

Figure 2.18 – Observation of initial process of WEEE dismantling for Small domestic appliances

The resulting fractions were stored in the containers previously selected and were weighted when necessary (whenever the container was full or when the processing operations were completed).

2.3.2.4 Registry of operating time and human resources per activity centre

Using the document previously prepared, the duration of the processing activities and the number and characteristics of human resources and the equipment involved in the operations were registered. The registry of activity times enabled to identify the ordinary and extraordinary events, like non planned stops by the machines or human operators and measure their impact on the processing capacity.

This data was essential to determine the effective processing capacity and also to understand how the processing line was organized and operated (e.g. number of shifts, number of human operators per shift, effective processing time, etc.). It also allowed to identify the misuse of the processing equipment by the operators (e.g. by-passing of specific processing steps) which could pose risks to the compliance with legal requirements on specific treatment and hinder the ability to achieve the legal reuse/recycling and recovery targets.

2.3.2.5 Weighting of the fractions

It was absolutely critical that all material fractions obtained in the test were weighted and the respective data was registered. In direct consequence of the number and volume of the containers selected, the weighting could be performed in two occasions:

- At the end of the operations, after all input material was treated or after a specific activity period was concluded;
- During the treatment operations performed on the WEEE, whenever the containers were full.

Figure 2.19 shows a typical weighting operation during a WEEE processing test: the material fraction is transported to the weighting equipment using a forklift and the weight data is registered.

Figure 2.19 – Weighting operation and data registry

In the event of any foreign material being detected during the treatment of WEEE, it was segregated, weighted and the respective net value deducted from the total weight of the input material.

As good practice to avoid any double counting or missing weightings, the fractions/containers that were already weighted would be stored away from the test premises, or the material would be transferred to containers that were not being used in the test.

In the end, the weight of the input material and the sum of the individual weight of all output fractions should be equal. The operations of weighting introduce uncertainty and differences in the mass balance were expected; overall, the discrepancy could not be more than 5% in order

for the mass balance accounting to be valid (WEEE Forum, 2008b). All tests performed in the research work complied with this threshold and were validated.

2.3.2.6 Characterization of the material composition of the fractions

After the completion of the processing operations, all output fractions were characterized regarding their material composition (percentage, in weight, of each of the materials present in the fractions). The material composition of each of the output fractions was determined *in-loco* through mass balance accounting (e.g. including separation of materials followed by individual weighting). Figure 2.20 show the process of determining the material composition of one output fraction: the materials are separated and weighted.

Figure 2.20 – Determining the material composition of output fractions

For some specific fractions (e.g. contaminated fractions) samples were taken for laboratorial analysis of their material content, to identify the presence of hazardous substances that were the target of legal requirements on treatment (e.g. mercury in glass and aluminium separated from fluorescent lamps) (see Figure 2.21). This was important to assess if the processing was being effective and to determine its technical performance.

Figure 2.21 – Collection of samples of glass and aluminium obtained from processing fluorescent lamps

2.3.3 Phase 3 – Assessment of the test results

After the processing of WEEE and monitoring were concluded, all the data was compiled and the calculations were made; in particular the weight of all output fractions was determined and compared with the weight of the input material. This was done straight after the processing was completed, with all the facts of the test still vivid in the memory of everyone and the material fractions obtained still physically available, so in case there were any discrepancies they could immediately be addressed and the reason for those could be identified to correct the problem (e.g. discrepancies in the mass balance accounting as a result of one recipient not being weighted or lacking of the characterization of the material composition for a given output fraction, in which case it could be done immediately or a sample could be taken for posterior characterization).

To finalize the work, a meeting would take place between the researcher and the people responsible from the PRO and from the operator. The different issues regarding the WEEE processing test would be addressed before the field work was officially completed.

Then, work in the office followed, including the calculations, analysis of results and reporting. Following the objectives of the execution of a WEEE processing test, the main results were:

- Diagram of operations for the WEEE processing technology;
- Weight of input material;
- Weight of individual output fractions obtained and respective subsequent operations and acceptors;
- Material composition of each individual output fraction obtained;
- Characterization of the resources used in processing the WEEE (human operators and equipment) and their operative specifications (e.g. throughput);
- Characterization of activities done in processing of WEEE (procedures and practices) and their operative specifications (e.g. activity times).

Figure 2.22 presents an example of a diagram of operations obtained from the execution of a WEEE processing test for treatment category D (Gas discharge lamps). It includes the intermediate and final processing operations (identified according with the European Waste List) (European Commission, 2000) and the material fractions (identified according with Annex III of Directive 2008/98/EC) (European Commission, 2008).

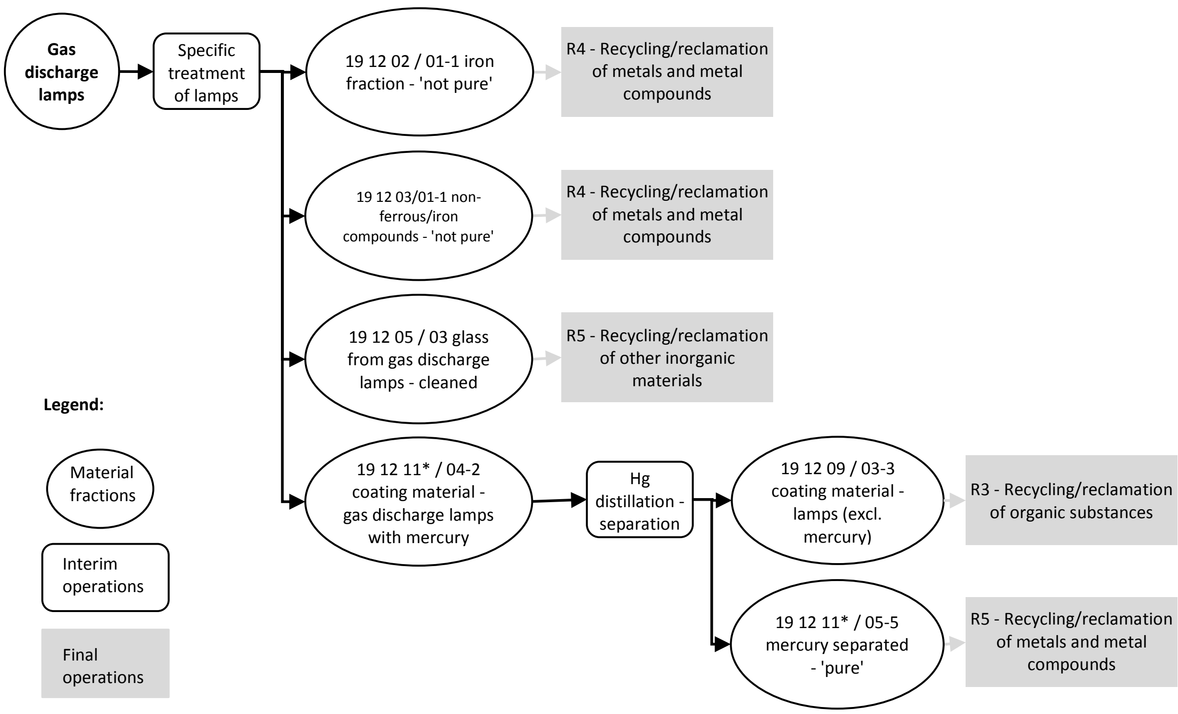


Figure 2.22 – Diagram of operations for processing lamps (based on technologies installed by operators in the Portuguese infrastructure)

Table 2.7 presents an example of the weight of output fractions obtained in one of the tests and the subsequent operations (notice: for confidentiality reasons the acceptors are not identified).

Table 2.7 – Weight of individual output fractions obtained from processing large household appliances and respective subsequent operations

EWL code (1)	Designation	% (in weight)	Operation code (2)
16 02 16 / 01	'iron-rich' fraction - dismantling	61.1%	R4
16 02 16 / 36	concrete 'parts' - dismantling	18.6%	R5
16 02 16 / 11-1	motors - large	12.0%	R4
16 02 16 / 31-2	plastics 'parts' dismantled from large (household) appliances (no Br-FR)	3.0%	R3
13 03 07*	(heat transmission) oils not containing PCBs	2.4%	R9
16 02 16 / 90	residual waste - dismantling	1.7%	D1
16 02 16 / 10	Cables (mix)	0.8%	R4
16 02 09* / 02-1	PCB (suspect) capacitors - small	0.2%	D15
16 02 16 / 13-1	printed circuit boards - low quality (no Br-FR, no components to be removed)	0.1%	R4
16 02 16 / 04	aluminium - metals 'pure' - dismantling	<0.1%	R4

Notes: (1) According with Annex III of Directive 2008/98/EC

(2) According with Commission Decision 2000/532/EC – European Waste List

Table 2.8 presents an example of the material composition results for the fraction of non ferrous metals obtained from lamp processing in one of the tests.

Table 2.8 – Material composition of non ferrous metal fractions from lamp processing

Output fraction	Image	Material composition
19 12 03 / 01-1 non-ferrous/iron compounds - 'not pure'		Aluminium 50.6% Copper 17.1% Glass 16.3% Plastics 16.0% Total 100.0%

Based on the data from the WEEE processing test the following results were calculated:

- Mass balance accounting (discrepancy between weight of input material and weight of output fractions);
- Effective percentages (in mass/mass) of WEEE reuse/recycling and recovery;
- Effective processing capacity (throughput) (in mass of WEEE per unit of time, e.g. kg/h or t/year).

2.3.4 Campaign of processing tests for WEEE

In order to collect data on the WEEE treatment and recovery technologies and fulfil the research objectives a broad and representative campaign of WEEE processing tests was executed in the Portuguese infrastructure. A significant initial task involved establishing a representative sample of processing operators and have them take part in the research work. This was probably one of the most difficult tasks in the course of the entire research work, considering the reserves by the operators regarding the disclosure of data on their internal processes and the technologies they operated.

In this context, the work was developed in close collaboration with AMB3E, the most significant PRO in Portugal which holds contracts with WEEE processing operators and was able to grant access to them. The execution of the WEEE processing tests was highly sensitive for the operators and for AMB3E, and for reasons of confidentiality the participants in the campaign behind the research work were not identified in the present document.

There were three main concerns regarding the collection of data that could provide valuable insight on the performance of WEEE treatment and recovery:

- WEEE is processed in five distinct treatment categories and each one of them had to be tested;
- In some treatment categories WEEE is processed using alternative technologies, and at least the most representative ones should be tested;
- Additionally, if there was the case of new and promising technologies being introduced by the operators during the time of the research work, they would have to be tested.

The research required a representative sample of WEEE processing operators to be tested in the Portuguese infrastructure. Ideally, the entire pool of WEEE processing operators in the Portuguese infrastructure would be tested, however this was both time consuming and it could be irrelevant in case the operators employed similar technologies and operational practices.

A very important aspect was the availability of the operators to be tested and the time to do the tests. The research work was developed to maximize the number of operators and the processing capacity tested within the time frame that was available to perform the tests. In the end, a total of 23 tests were executed covering the processing of all five distinct WEEE treatment categories and the technologies installed in the Portuguese infrastructure.

Table 2.9 illustrates the campaign of tests executed. It began in 2007, and until 2010 it was possible to execute most of the tests for the Portuguese infrastructure, in particular to conclude those regarding the categories A, B and D. The tests for the treatment categories C and E were

completed by 2012. In the case of treatment category C, new technologies were installed and additional tests were performed. In the case of treatment category E, there was an update to the technology that required experimental evidence. In both cases, the operators were responsible for processing high amounts of WEEE within the Portuguese infrastructure and field work proved necessary to have a representative characterization.

Table 2.9 –WEEE processing tests performed

Year	Large household appliances (# tests)	Cooling and freezing appliances (# tests)	Small domestic appliances (# tests)	Gas discharge lamps (# tests)	CRT televisions and monitors (# tests)	Total
2007	-	1	1	1	1	4
2008	4	-	3	-	1	8
2009	3	1	2	-	-	6
2010	1	-	-	1	-	2
2011	-	-	-	-	-	-
2012	-	-	2	-	1	3
Total	**8**	**2**	**8**	**2**	**3**	**23**

Each test involved the processing of a batch amount of WEEE per category. On average, the amount of WEEE processed per test was over 10 tons, accounting for a total more than 246 tons for the entire campaign. Table 2.10 presents the summary of the amounts of input material processed in the tests per treatment category during the campaign.

Table 2.10 – Amounts of input material per WEEE processing test

Amount	Large household appliances (Kg)	Cooling and freezing appliances (Kg)	Small domestic appliances (Kg)	Gas discharge lamps (Kg)	CRT televisions and monitors (Kg)	Total
Minimum per test	6876	17420	6094	3150	3162	-
Maximum per test	13968	19268	21484	7595	7856	-
Average per test	11671	18344	11337	5373	4906	10705
Total campaign	**93369**	**36688**	**90694**	**10745**	**14718**	**246214**

The entire campaign of WEEE processing tests lasted for almost as long as the entire period of the research work: on one hand it was necessary to have a broad and representative sample of WEEE processing operators, processing techniques and technologies, and on the other there were constraints related with the availability of the operators, that limited the time frame for this stage of the research work.

Overall, the total duration of the field work, or phase 2, in the campaign of WEEE processing tests was 144 working days or 6.3 days per test, on average (see Table 2.11). Before this, a variable period of time would occur to get approval by the operator to execute the WEEE processing test. Once there was approval, on average 2 weeks were necessary to prepare for each test, including the discussion of the protocol for WEEE processing tests, the characterization of the processing technology installed, the establishment of the sample of input material, the identification of the expected output fractions to be obtained, the preparation of data registry documents and other administrative data such as accreditations.

After the field work was concluded, the closing stages involved on average 1 week per test to process and analyse all the data, make any additional clarifications with the operator and elaborate the final report.

Table 2.11 – Duration of the field work in the WEEE processing tests

Year	Large household appliances (days)	Cooling and freezing appliances (days)	Small domestic appliances (days)	Gas discharge lamps (days)	CRT televisions and monitors (days)	Total
2007	-	4	8	3	3	18
2008	22	-	44	-	3	69
2009	17	3	16	-	-	36
2010	7	-	-	4	-	11
2011	-	-	-	-	-	-
2012	-	-	8	-	2	10
Total	**46**	**7**	**76**	**7**	**8**	**144**

Two aspects were continuously assessed during the campaign of WEEE processing tests: the number of operators and the processing capacity tested per WEEE treatment category. The results were continuously compared to the total number of operators and processing capacity in the Portuguese infrastructure as the research work tried to ensure a solid characterization of the end-of-life processing of WEEE.

Figure 2.23 presents the ratio of the number of operators in the Portuguese infrastructure per category of WEEE, identifying those that were tested and those that were not tested in the research work. In Figure 2.24 the processing capacity of the Portuguese infrastructure is presented per treatment category, identifying the percentage which was tested and the percentage that was not tested.

Concerning treatment category A (Large household appliances), 8 processors were tested, representing 55.4% of the total installed capacity in the Portuguese infrastructure. The remaining 11 operators were not tested due to time constraints and the availability of the

operators to be part of the study. Nevertheless, the main technologies, manual and mechanical, that are used to process large household equipment were tested.

Regarding WEEE from treatment category B (Cooling and freezing appliances), the Portuguese infrastructure is composed of 3 operators, 2 of which were tested, representing approximately 2/3 of the total installed capacity. They use similar processing technologies.

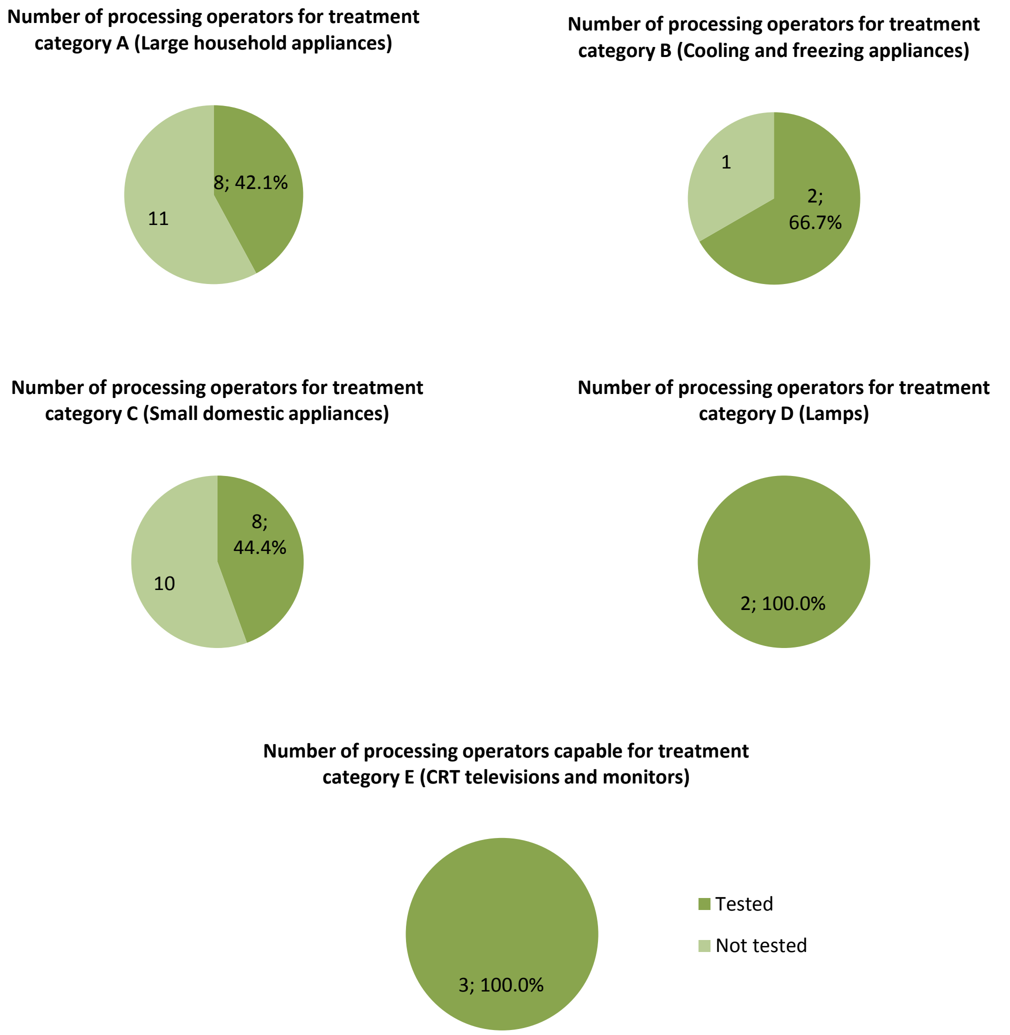


Figure 2.23 – Number of operators in Portuguese infrastructure tested in the research work

Small domestic appliances are processed by dismantling but some operators adopt mechanical processing technologies. During the research work a total of 8 operators were tested, including all types of processing technologies, covering 72.0% of the total installed capacity.

Lamps are one of the WEEE treatment categories classified as hazardous due to the presence of mercury, a metal that can affect human health by causing severe damage to the nervous system (Environmental Protection Agency, 2012). Consequently, lamps are treated with specific technologies to separate and collect the mercury as well as to promote the recovery of materials

and minimize disposal. There are 2 operators in the Portuguese infrastructure and both were tested in the course of the research work.

WEEE of treatment category E (CRT televisions and monitors) is also classified as hazardous, essentially because of the lead content in the tube glass and also the phosphorous coating in the inside of the screen. The WEEE is processed using specific technologies, with a combination of manual and mechanical processes to separate the leaded glass and the phosphorous powders from the remaining CRT materials. In the Portuguese infrastructure there are 3 operators and all were tested in the research work.

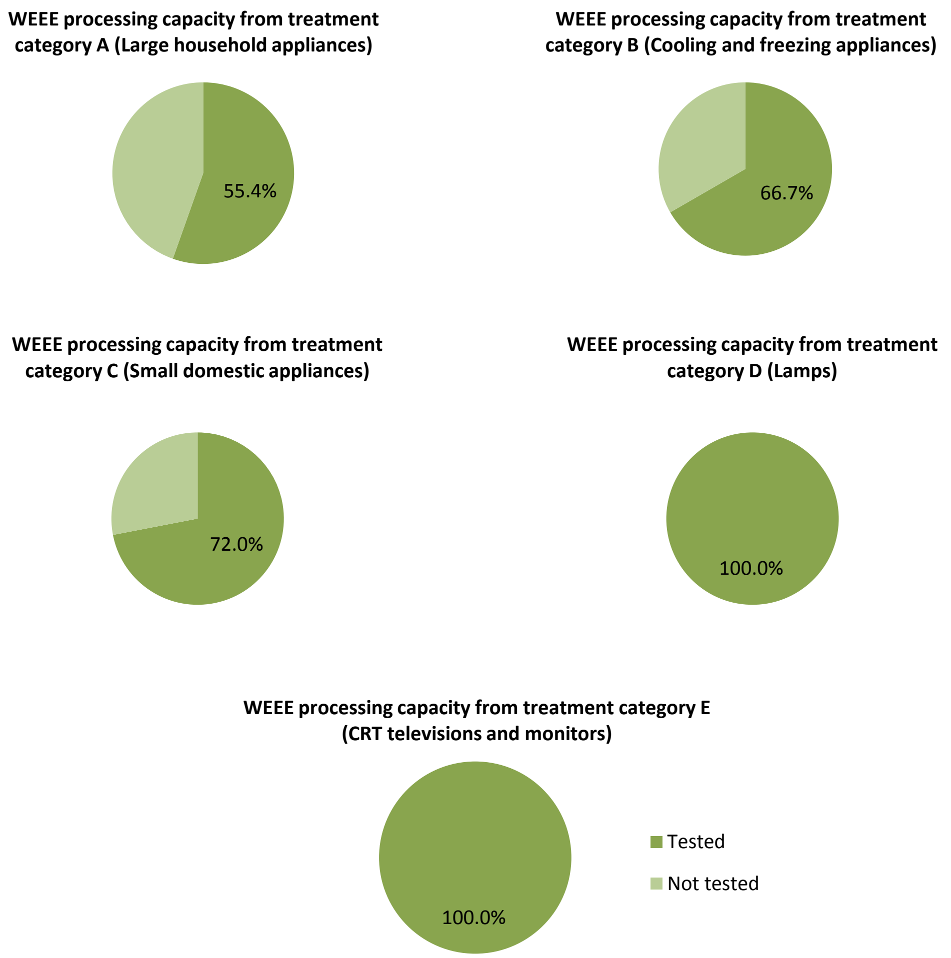


Figure 2.24 - Capacity of Portuguese infrastructure that was tested in the research work

Considering the number and processing capacity of the operators that were tested, the campaign of WEEE processing tests within the research work resulted in the characterization of a very significant part of the Portuguese infrastructure for WEEE processing.

Regarding the remaining operators in the Portuguese infrastructure that were not tested, the respective operations were characterized based on data provided by themselves. This data was not verified by the researcher by means of experimental testing, and so it could represent a limitation in terms of its quality and accuracy.

3 Developing a model of the processing of WEEE

3.1 Modelling individual operations

One of the main objectives of the research was to develop models to characterize the end-of-life processing of the WEEE considering the technical, economic and environmental aspects.

The end-of-life processing chain for WEEE is made of successive operations that receive input material and process it to produce outputs that are subsequently processed in downstream operations, until reaching a final operation where it is recovered and/or eliminated. Following the research objective, it was necessary to have a systematic approach that could provide the closest possible representation of the reality in the form of the models of the operations and the technologies used in the treatment and recovery of WEEE. Two different types of operations were considered to develop the models, as follows:

- Intermediate operations: this type of operation receives input material, process it and produce a number of outputs that are sent to downstream operations;
- Final operations: this type of operation receives input material, may eventually do some processing and then incorporate it into final applications of recovery – including reuse, recycling and energy recovery – or elimination – including incineration without energy recovery and disposal in landfill.

When output fractions from an intermediate operation are sent to the subsequent operation, this can require transportation if both operations are performed in different locations.

Figure 3.1 presents a schematic view of a simplified end-of-life processing chain for WEEE, where the different types of operations can be identified.

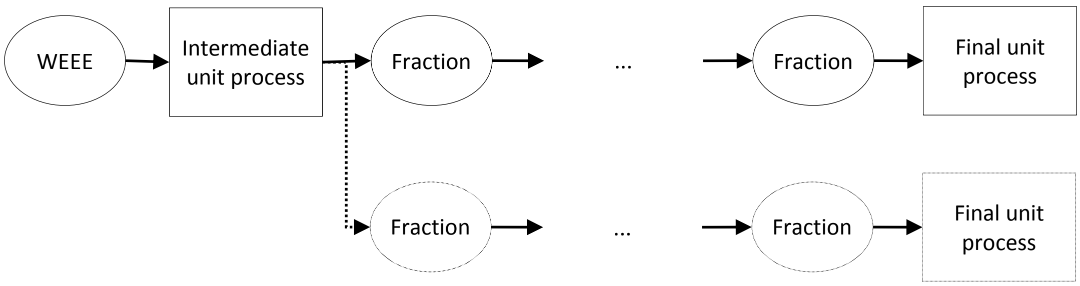


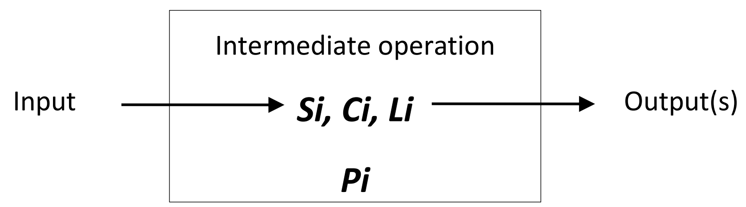
Figure 3.1 – Simplified generic diagram of end-of-life processing chain for WEEE

The specific model of each operation was developed to incorporate the technical, economic and environmental aspects that characterize it. In the following subsections, the models of each of the type of operations are described.

3.1.1 Intermediate operations

The intermediate operations are characterized by having both input and output of mass. The input material is converted in to output fractions, in the number, type and with the material composition which was determined by the end-of-life processing tests and with the use of bibliographical sources and survey with providers of end-of-life processing technologies. Subsequently, each output fraction is processed in a downstream operation, which can be done by the same operator in the same facilities or it can be done by other operators and/or in facilities in a distinct location, in which case the fraction has to be transported.

The technical aspects related with the mass balance constituted the basis for the models of the operation, which also included the economic and the environmental aspects. Figure 3.2 represents a schematic view of an intermediate operation.



Si = separation efficiency, Ci = cost, Li = environmental impact and Pi = processing capacity

Figure 3.2 - Model of a generic intermediate operation

Table 3.1 presents a (non exhaustive) list of intermediate operations that were modelled in the research work.

Table 3.1 – Examples of intermediate operations

Intermediate operations	
Dismantling / sorting	Plastics conditioning
Large shredder / separation	Conditioning of high caloric material
Shredder for cooling and freezing appliances/separation	Conditioning of waste
Medium shredder / separation	Wood conditioning
Special treatment of gas discharge lamps	Special treatment of radioactive appliances/components
Fine shredder / separation	Special treatment of asbestos appliances/components
Separation	Special treatment of flat panel display appliances/components
Manual separation	Special treatment of Hg components
Manual sorting	Hg distillation - separation
CRT splitting / crushing	Special treatment of toner cartridges
CRT glass grinding / cleaning	Battery sorting
Other glass conditioning	Battery separation
Mineral conditioning	Preparing for reuse

Notes: Included in the global model based on the technologies installed by the operators in the Portuguese infrastructure and downstream.

3.1.1.1 Technical aspects

Each operation was characterized using data from the WEEE processing tests regarding the mass and material composition of the input and outputs based on a set of eleven material categories, as presented in Table 3.2.

Table 3.2 – Material categories

Material categories	Description
Ferrous metals	Includes all ferrous metals, elemental or alloy (e.g. steel).
Aluminium	Includes aluminium and aluminium alloys.
Copper	Includes copper and copper alloys (e.g. brass).
Other metals	Includes all metals that are excluded from the previous categories, including precious metals (e.g. gold, silver) or metals with high hazardousness (e.g. mercury)
Plastics	Includes all thermoplastics and thermosets.
Rubber	Includes all elastomers.
Textile	Includes synthetic and natural fibres used as textile.
Cement	Includes cement and other non-metallic minerals.
Glass	Includes glass and other mineral based translucent materials.
Wood	Includes wood and wood derived materials.
Other	Includes all other materials that are excluded from previous categories.

Table 3.3 presents an example of the material composition of a fraction of "small electric motors" represented in the eleven categories of materials established in the models.

Table 3.3 – Material composition of "small electric motors"

Material categories	% (in mass)
Ferrous metals	47.2%
Aluminium	4.1%
Copper	41.0%
Other metals	<0.1%
Plastics	7.5%
Rubber	<0.1%
Textile	0.0%
Cement	0.0%
Glass	0.0%
Wood	0.0%
Other	<0.1%
Total	**100.0%**

The input of any operation can be mathematically formulated as follows:

Equation 3.1 – Input of operations

$$I_i \text{ (in tons)} = (I_1, \ldots, I_i)$$

where i = 1, .., 11, categories of materials

For an intermediate operation, the core technical aspect is the efficiency of separation per material per output fraction, which transforms the physical inflows per material category into physical outflows per material category and per output fraction. The separation efficiency was determined in the course of the field work from the characterization of the material composition of the input and of the respective output fractions as well as with the use of bibliographical sources and survey with providers of end-of-life processing technologies.

Table 3.4 presents an example of the efficiencies of separation obtained for the operation "shredding and separation" of "small electric motors" in the four respective output fractions.

Table 3.4 – Efficiencies of separation of "shredding and separation" of "small electric motors" in to the respective output fractions (in percentage in mass)

Material categories	'iron-rich' fraction	'aluminium-rich' fraction	'copper-rich' fraction	residual waste	Total
Ferrous metals	89.4%	5.1%	4.7%	0.8%	100.0%
Aluminium	3.3%	92.7%	3.0%	1.0%	100.0%
Copper	2.3%	4.4%	93.1%	0.2%	100.0%
Other metals	1.8%	0.5%	0.1%	97.6%	100.0%
Plastics	0.0%	0.0%	0.0%	100.0%	100.0%
Rubber	0.0%	0.0%	0.0%	100.0%	100.0%
Textile	0.0%	0.0%	0.0%	100.0%	100.0%
Cement	0.0%	0.0%	0.0%	100.0%	100.0%
Glass	0.0%	0.0%	0.0%	100.0%	100.0%
Wood	0.0%	0.0%	0.0%	100.0%	100.0%
Other	0.0%	0.0%	0.0%	100.0%	100.0%

The efficiencies of separations are defined in a matrix of eleven (from the number of categories of materials) by the number of output fractions, depending on the characteristics of the respective operation. The matrix of efficiencies of separation used in the models is defined as follows.

$$Si_{n,i} \text{ (in percentage)} = \begin{pmatrix} Si1,1 & \dots & Si1,i \\ \dots & & \dots \\ Sin,1 & \dots & Sin,i \end{pmatrix}$$

where n = 1, …, 11 categories of materials and i = 1, …, number of output fractions

The models of the intermediate operations regarding the technical aspects have the following mathematical formulation shown in Equation 3.2.

Equation 3.2 – Modelling technical aspects of intermediate operations

$$I \times Si = Osi,$$

where I is the input of operation (in tons), Si is the matrix of efficiencies of separation (in percentage) and Osi is the matrix of outputs of the process (in tons).

The processing capacity corresponds to the amount of material that the equipment performing the intermediate operation can process in a given time. It was modelled based on data obtained from the campaign of end-of-life processing tests, from bibliographical sources and survey with providers of end-of-life processing technologies. This is a determining factor of the performance of a process and Equation 3.3 presents the mathematical formulation.

Equation 3.3 – Processing capacity

$$Pi = \frac{I}{t}$$

where Pi is the processing capacity (in tons per hour), I is the total amount of input (in tons) and t is the processing time (in hours)

The processing capacity constituted an important variable to determine the specific cost of processing.

3.1.1.2 Economic aspects

The end-of-life processing of the input of WEEE translates in to a cost of processing. The economic aspects of each operation were accounted for in the models and the processing cost was calculated considering the items that are included in Table 3.5.

Table 3.5 – Cost items considered for calculating the processing cost

Cost item	Description
Investment cost	Includes the cost with the acquisition/rental of the terrain and facilities (e.g. industrial buildings and offices), the additional infrastructural support systems (e.g. compressed air distribution system), the processing support equipments (e.g. forklifts) and most importantly the equipments of the processing technologies (e.g. shredder, magnetic separator, etc.) and also training for human resources.
Capital cost	Includes the cost with capital (interest), either associated with loans or in alternative the lost capital revenue associated with doing investment with own capital.
Operational cost	Includes the use and maintenance of the terrain and facilities, the support systems, the support equipments and the processing technologies, most notably the consumption of energy and labour to process the WEEE.

Table 3.6 presents an example of the modelling of the processing cost for the operation "shredding and separation" of "small electric motors". The specific cost is calculated considering the annual processing capacity of the operation.

Table 3.6 – Processing cost for "shredding and separation" of "small electric motors"

Cost items	Cost		Calculation data			
	value	unit	value	unit	value	unit
Facilities (1)						
Terrain	5000	euro	500	m^2	10	euro/ m^2
Industrial building	50000	euro	200	m^2	250	euro/ m^2
Offices	12500	euro	50	m^2	250	euro/ m^2
Impermeable park	15000	euro	250	m^2	60	euro/ m^2
Weight scale	10000	euro	1	units	10000	euro/unit
Compressed air distribution system	4000	euro	100	m	40	euro/m
Compressor	5000	euro	1	units	5000	euro/unit
Compressed air tank (400 litres)	2000	euro	1	units	2000	euro/unit
Total	**103500**	**euro**				
Annual building maintenance (includes lighting)	1875	euro	3%	% of investment		
Annual maintenance of complementary equipments	1050	euro	5%	% of investment		
Total	**2925**	**euro**				
Equipments (2)						
Processing						
Forklift	10000	euro	1	units	10000	euro/unit
Shredder	1000000	euro	1	units	1000000	euro/unit
Hammers	50	euro	1	units	50	euro/unit
Pneumatic screwdrivers	100	euro	1	units	100	euro/unit
Containers	400	euro	4	units	100	euro/unit
Big-bags	100	euro	4	units	25	euro/unit
Total	**1010650**	**euro**				
Annual maintenance of forklift (includes fuel)	500	euro	5%	% of investment		
Annual maintenance of tools (includes consumables)	8	euro	5%	% of investment		
Annual maintenance of processing equipments (includes energy consumption)	50000	euro	5%	% of investment		
Total	**50508**	**euro**				

Cost items	Cost		Calculation data			
	value	unit	value	unit	value	unit
Safety						
Overalls	350	euro	7	units	50	euro/unit
Gloves (pair)	140	euro	7	units	20	euro/unit
Safety boots (pair)	350	euro	7	units	50	euro/unit
Safety goggles (pair)	140	euro	7	units	20	euro/unit
Masks	70	euro	7	units	10	euro/unit
Total	**1050**					
Labour (3)						
Forklift driver	8040	€/year	1	operators	500	euro/month
Operators	48240	€/year	6	operators	500	euro/month
Technical supervisor	16080	€/year	1	technical supervisors	1000	euro/month
Manager	32160	€/year	1	managers	2000	euro/month
Total	**104520**	**€/year**				
Summary						
Facilities						
Facilities	4140	euro/year	25	years		
Maintenance	117	euro/year	25	years		
Equipments						
Forklift	2000	euro/year	5	years		
"heavy duty" equipments	200080	euro/year	5	years		
"light duty" equipments	125	euro/year	2	years		
Annual maintenance of forklift (includes fuel)	100	euro/year	5	years		
Annual maintenance of tools (includes consumables)	4	euro/year	2	years		
Annual maintenance of processing equipments (includes energy consumption)	10000	euro/year	5	years		
Safety	525	euro/year	2	years		
Labour						
Forklift driver	8040	euro/year				
Operators	48240	euro/year				
Technical supervisor	16080	euro/year				
Manager	32160	euro/year				
Processing cost	**321611**	**euro/year**				
Processing cost	**32.2**	**euro/t**	**10.000**	**t/year**		

Notes: (1) Dimensions and equipment according with average facilities of operators in the Portuguese infrastructure; unit cost based on data provided by operators and consultation with facilities providers.

(2) Number and type of equipment based on the operators in the Portuguese infrastructure; unit cost based on data provided by operators and consultation with equipment providers (e.g. Balcan, Boliden, BRT Recycling Technologies GmbH, Cogelme, Eldan Recycling, Lessine Industries, Metso, MeWa, MRT System International, Titech, etc.).

(3) Human resources based on the operators in the Portuguese infrastructure; unit cost based on specialist estimation.

Different operations may have different determining factor for their economic performance. In order to ensure the comparison between different operations, the processing cost was calculated and then converted in to fixed and variable cost:

- Fixed cost: includes all costs that do not vary with the amount of WEEE being processed in the operation (e.g. costs with facilities, acquisition of equipment, bank loans, salaries, preventive maintenance, etc.); and
- Variable cost: includes all costs that vary with the amount of WEEE being processed in the operation (e.g. energy cost, reparative maintenance of equipment, etc.).

Table 3.7 – Fixed and variable processing cost for "shredding and separation" of "small electric motors"

Cost items	Cost		Calculation data	
	value	unit	value	unit
Processing cost	**321611**	**euro/year**		
Fixed cost	217091	euro/year		
Variable cost	104520	euro/year		
Processing cost	**32.2**	**euro/t**	**10000**	**t/year**
Fixed cost	21.7	euro/t	10000	t/year
Variable cost	10.5	euro/t	10000	t/year

The cost of processing the input of WEEE in each intermediate operation is given by Equation 3.4.

Equation 3.4 – Modelling the economic cost of intermediate operations

$$I \times Ci = Oci,$$

where I is the total amount of the input of WEEE to the operation (in tons), Ci is the specific cost of performing the intermediate operation to the WEEE (in euro per ton) and Oci is the cost of processing the input of WEEE (in euro).

As the output fractions from one operator are sent to the subsequent operators, in general there is a monetary flow associated with the mass flow, which can be either cost or revenue, depending on the market value of the output fraction. This value should normally reflect the intrinsic economic value of the fraction and include a profit margin.

Considering two successive operators, if the monetary flow is for example revenue in the perspective of the sender, it will be a cost in the perspective of the acceptor, and vice-versa. Overall, considering the economic balance of both operators together, the monetary flows between them cancel each other and do not affect the global economic balance. Following this, in the development of the economic models the monetary flows between successive operators were not considered.

By excluding the trade between successive operators from the calculation of the economic balance, the profit margins and the economic inefficiencies associated with trade (e.g. speculation) are ruled out and the calculation becomes more close to the intrinsic economic value of the processing of WEEE. This presents an advantage in terms of determining the effective economic value of ensuring the treatment and recovery of WEEE according with the

legal responsibility of producers of EEE. As referred in the introductory chapter, the producers of EEE, through the representative PRO's, have to provide financial assistance to ensure that WEEE is properly treated and the reuse/recycling and recovery legal targets are achieved. However, they should only provide for the net unbalance between cost and revenue considering the fair economic performance of the end-of-life processing infrastructure while also excluding economic inefficiencies, such as price speculation or unfair profit margins.

3.1.1.3 Environmental aspects

Although the technical models allowed the calculation of the reuse/recycling and recovery rates, these are very limited indicators in what concerns the assessment of the environmental performance of WEEE treatment and recovery. It was the objective of the research work to have more detailed environmental performance assessment, based on more specific data that could also provide insight on the significance of the end-of-life stage of WEEE in a life cycle perspective.

Life Cycle Assessment is a methodological tool used to quantitatively analyse the life cycle of products/activities. According to the International Organization for Standardization (ISO) norm 14040, LCA is the process of compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. This series of ISO norms defines a framework and establishes the principles and requirements for LCA studies. ISO 14040 and 14044 provide a generic framework.

The basis for LCA techniques is the concept of life cycle, during which products have direct and indirect impacts on the environment, from the first stages of raw materials extraction, through the production, distribution and use stages, until the end-of-life stages. LCA tries to assess the environmental impacts of a product during its entire life cycle, from the inputs and outputs, respectively from and to the natural environment.

LCA methodology comprises a set of different methods and approaches within a general framework. As mentioned in IS0 14040, "there is no single method for conducting LCA's ..." (ISO, 1997). It is not possible to define the rigid methodological rules for all aspects of LCA because the scope, boundaries, and level of detail will depend on the subject and intended application of the study. The IS0 14040 and subsequent standards distinguish four interrelated phases in the LCA framework:

- Goal and scope definition: this is considered by some the most important of all phases in LCA (Lindfors, 1995). It is where the detailed framework of the study is defined. When defining the goal of an LCA study, some issues must be questioned, such as the reason for the study, the object of the study and the purpose for the results. Thus, the goal shall objectively state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated (ISO, 1997).
  An important function of the present phase is to establish the indispensable information to tackle the goal. The purpose of the scope definition is to identify and to define the object of the assessment and to limit it to include what is significant for the LCA goal.

Typically, it involves identifying the functions of the assessed products or services, system boundaries (time and space), functional unit, data requirements, alternative products or services, key assumptions, and limitations of the study (adapted from ISO, 1997).

- Inventory analysis: this concerns data collection and calculation of results for the functional unit. The issues of great concern for the inventory analysis are planning data quality and collection, and checking data for all the processes of the product life cycle (Bhander et al., 2003).

  Interpretations may be drawn from these data, depending on the goals and scope of the LCA. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study (ISO, 1997).
- Impact assessment: constitutes one important task of life cycle impact assessment, as it deals with impacts on the environment, resource consumption, and possible impacts on the working environment. The impact assessment phase is divided into the following four steps:
  - Classification;
  - Characterization;
  - Normalization;
  - Weighting.

  The data inventory lists and organizes the information on inputs and outputs of the processes involved in the product life cycle. However, from that data it is not possible to directly measure the environmental impacts. For that matter, the inventory data has to be formatted, and that is managed with both Classification and Characterization steps. Classification involves the assignment of emissions to specific environmental impact categories. Characterization entails the calculations of category indicator results for the referred impact categories. By assigning specific weighting values to the environmental data in the inventory, a correspondence is established between the inventory and the environmental categories. However, no relation is defined between the environmental categories. Generally, the weighting values assigned to the inventory environmental data are calculated by normalizing the information to a reference unit value (Bhander et al., 2003).
- Interpretation: where the results are interpreted considering the LCA conditions.

In general, after goal and scope has been determined, data has been collected, and an inventory result is calculated. This inventory result is usually a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is difficult. A Life Cycle Impact Assessment (LCIA) procedure, such as the ReCiPe Midpoint method, version 1.07 July 2012 (Goedkoop et al., 2012) method is designed to help with this interpretation.

ReCiPe uses an environmental mechanism as the basis for the modelling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage

to human health, ecosystems and resources. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct.

From this example it is clear that the longer one makes this environmental mechanism the higher the uncertainties get. The radiative forcing is a physical parameter that can be relatively easily measured in a laboratory. The resulting temperature increase is less easy to determine, as there are many parallel positive and negative feedbacks. The understanding of the expected change in habitat is also not complete. The benefit of taking only the first step is the relatively low uncertainty and so this was the approach followed in the research to develop the environmental models for the different processes of WEEE treatment and recovery using an auxiliary LCA tool and the ReCiPe method. Table 3.8 lists the seventeen midpoint indicators.

Table 3.8 – Categories of environmental impact assessment (according with ReCiPe method from PRé Consultants (2008))

#	Categories
1	Climate Change HH
2	Climate Change ED
3	Ozone Depletion HH
4	Terrestrial Acidification ED
5	Freshwater Eutrophication ED
6	Human Toxicity HH
7	Photochemical Oxidant Formation HH
8	Particulate Matter Formation HH
9	Terrestrial Ecotoxicity ED
10	Freshwater Ecotoxicity ED
11	Marine Ecotoxicity ED
12	Ionising Radiation HH
13	Agricultural Land Occupation ED
14	Urban Land Occupation ED
15	Natural Land Transformation ED
16	Mineral Resource Depletion RA
17	Fossil Fuel Depletion RA

Notes: HH – Damage to human health; ED – Damage to ecosystem quality; RA – Damage to mineral and fossil resource availability.

The different intermediate operations had the respective environmental performance modelled. Table 3.9 presents an example of the environmental impacts calculated for the operation “shredding and separation” per ton of processed “small electric motors”.

Table 3.9 – Environmental impacts of "shredding and separation" of "small electric motors"

#	Categories	Normalization points per ton
1	Climate Change HH	0.0172353447
2	Climate Change ED	0.0022980581
3	Ozone Depletion HH	0.0000005576
4	Terrestrial Acidification ED	0.0000032099
5	Freshwater Eutrophication ED	0.0000005651
6	Human Toxicity HH	0.0003468289
7	Photochemical Oxidant Formation HH	0.0000019744
8	Particulate Matter Formation HH	0.0078731604
9	Terrestrial Ecotoxicity ED	0.0000076783
10	Freshwater Ecotoxicity ED	0.0000000117
11	Marine Ecotoxicity ED	0.0000000002
12	Ionising Radiation HH	0.0000009831
13	Agricultural Land Occupation ED	0.0000262261
14	Urban Land Occupation ED	0.0000190981
15	Natural Land Transformation ED	0.0000578892
16	Mineral Resource Depletion RA	0.0000111454
17	Fossil Fuel Depletion RA	0.0470073600
-	**Total**	**0.0748900912**

Because the results are in normalization points, it is possible to obtain the sum of the environmental impacts in the distinct impact categories according with the ReCiPe methodology. The environmental impacts of processing the input of WEEE in each intermediate operation are given by Equation 3.5.

Equation 3.5 – Modelling the environmental impacts of intermediate operations

$$I \times Li = Oli,$$

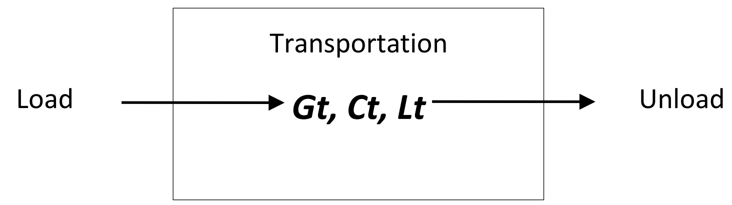
where I is the total amount of the input of WEEE to the operation (in tons), Li is the specific environmental impacts of performing the operation (in normalization points per ton) and Oli is the environmental impacts of processing the input of WEEE (in normalization points).

3.1.2 Transportation operations

Because the operations involved in the entire end-of-life processing of WEEE can be performed in facilities in distinct locations, including various countries, the transportation was also modelled.

- Transportation: this type of operation receives the material fractions from one intermediate operation in a designated location and transport it to another location, where it will subsequently be subjected to another operation.

Transportation can be done by road, in trucks, by sea, using container ships, or by railroad using container trains. The most common means used to transport WEEE and its fractions are trucks, especially within the continental territories (e.g. Europe, United States of America, and Asia). Figure 3.3 represents a schematic view of an intermediate operation.



Gt = cargo efficiency, Ct = cost and Lt = environmental impact

Figure 3.3 - Model of a generic transportation operation

3.1.2.1 Technical aspects

The most important technical aspects of a transportation operation are the amount of cargo that is transported and the distance travelled. Both were considered in the models that were developed.

The amount of cargo transported can be limited by the volume of the container or by the weight that the vehicle can pull. In the case of trucks, there is a limitation by volume and weight, while in the case of containers ships and trains the only limitation is by volume. Table 3.10 summarizes the specifications of the different types of transportation operations that were considered in the models.

Table 3.10 – Limitations to amounts being transported

Mode of transportation		Specifications (1)	
		Volume (m^3)	**Weight (t)**
By road	Truck (semi-trailer)	60.0	25.0
By sea	Container ship (twenty foot equivalent unit (TEU))	38.5	-
By railroad	Container train (twenty foot equivalent unit (TEU))	38.5	-

Notes: (1) For standardized semi-trailer truck and twenty foot equivalent ship and train containers.

When a fraction that is obtained from an operation has to be transported to the next operation, it was necessary to determine the maximum amount of the respective fraction that could be transported for the given mode of transportation that was selected. This was done using data on the specific weight of each output fraction using data from the end-of-life processing tests as well as data from bibliographical sources. The objective was to determine the number of trucks or containers necessary to transport each ton of the specific fraction. Equation 3.6 to Equation 3.10 present the respective mathematical formulations.

Equation 3.6 – Number of containers per ton of fraction

$$Nc = \frac{1}{d \times maxV}$$

where Nc is the number of containers per ton, d is the specific weight of the fraction (in ton per m^3) and max V is the maximum cargo volume per container (in m^3 per container).

In order to determine the number of truck loads, it is necessary to assess if the cargo capacity of the truck is reached, either by the volume or by the weight. The volume of a full weight load is calculated as follows:

Equation 3.7 – Volume of the full weight load

$$Vmw = \frac{maxW}{d}$$

$$(\text{Vmw} < 60\text{m}^3)$$

where Vmw is the volume (in m^3) of the maximum weight of a truck load, maxW is the maximum weight of a truck load (in tons) and d is the specific weight of the fraction (in tons per m^3)

The weight of a full volume load is calculated as follows:

Equation 3.8 – Weight of the full volume load

$$Wmv = d \times maxV$$

$$(\text{Wmv} < 25\text{t})$$

where Wmv is the weight (in tons) of the maximum volume of a truck load, maxV is the maximum volume of a truck load (in m^3) and d is the specific weight of the fraction (in tons per m^3)

If Vmw > 60 and Wmv < 25, the load is limited by the volume and the number of truck loads is calculated by:

Equation 3.9 – Number of truck loads per ton of fraction limited by the volume capacity

$$Nt = \frac{1}{d \times maxV}$$

where Nt is the number of truck loads per ton, d is the specific weight of the fraction (in ton per m3) and maxV = 60 is the maximum cargo volume per container (in m3 per container).

If Vmw < 60 and Wmv > 25, the load is limited by the weight and the number of truck loads is calculated by:

Equation 3.10 – Number of truck loads per m³ of fraction limited by the weight capacity

$$Nt = \frac{d}{maxW}$$

where Nt is the number of truck loads per m³, d is the specific weight of the fraction (in ton per m3) and maxW = 25 is the maximum cargo weight per container (in ton per container).

Regarding the other variable of the transportation operation, the distance travelled, it was determined based on the data of the locations of the sender and of the acceptor of each fraction. This type of data was collected in the course of the end-of-life processing tests done for the Portuguese infrastructure and was complemented with the survey on the downstream operators that receive and further process the fractions obtained from the Portuguese infrastructure.

3.1.2.2 Economic aspects

The costs related with the transportation of output fractions to subsequent operations in different locations used the results of modelling the technical aspects, namely the number of truck loads or number of containers per ton of fraction to be transported. This equals to the number of trips to be done per ton, and was used to calculate the total distance travelled for the respective mode of transportation.

A set of specific transportation cost factors were used based on the data obtained from commercial logistics operators. Service prices for road transportation are given in euro per kilometre, considering the full truck load transportation between Portugal and a destination in Europe. For sea transportation the prices are given in euro by container, assuming fixed load and unload locations, respectively in Portugal and in China. Finally, the railroad transportation prices are given in euro per ton per kilometre, for transportation between Portugal and a destination in Europe.

Table 3.11 presents the cost factors that were accounted for in the models.

Table 3.11 – Cost factors considered to calculate the processing cost

Mode of transportation		Specific cost factor (1)	
		value	**unit**
By road	Truck (semi-trailer)	2.21	euro/km
By sea	Container ship (twenty foot equivalent unit (TEU))	827.5	euro/container
By railroad	Container train (twenty foot equivalent unit (TEU))	0.05	euro/t.km

Notes: (1) According with data by service providers (e.g. DB Schenker, Maersk Line and CEVA Logistics).

The cost of transportation of a designated amount of a fraction using the alternative modes is given by Equation 3.11 to Equation 3.13.

Equation 3.11 – Cost of transportation by road

$$Ctroad = A \times Ctr \times dist \times Nt$$

where Ctroad is the total cost of transportation by road (in euro), A is the total amount to be transported (in ton), Ctr is the specific cost factor (in euro/km), dist is the distance per truck load (in kilometres/truck load) and Nt is the number of truck loads per ton.

Equation 3.12 – Cost of transportation by sea

$$Ctsea = A \times Cts \times Nc$$

where Ctsea is the total cost of transportation by sea (in euro), A is the total amount to be transported (in ton), Cts is the specific cost factor (in euro/container) and Nc is the number of containers per ton.

Equation 3.13 – Cost of transportation by railroad

$$Ctrailroad = A \times Ctrr \times d$$

where Ctrailroad is the total cost of transportation by railroad (in euro), A is the total amount to be transported (in ton), Ctrr is the specific cost factor (in euro/ton.kilometre) and d is the distance travelled (in kilometres).

3.1.2.3 Environmental aspects

The environmental aspects of the transportation operations were considered similarly as they have been for the intermediate operations: for each of the modes of transportation the respective specific environmental impacts were calculated using LCA and the ReCiPe methodology to assess the impacts. Table 3.12 presents an example of the environmental impacts of road transportation using a truck calculated for “copper rich fraction” obtained from processing electric cables.

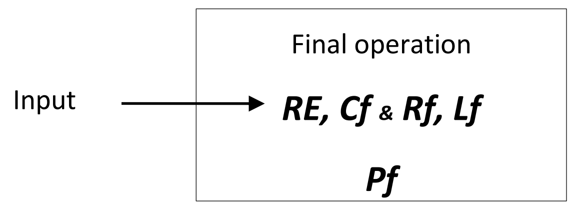
Table 3.12 – Environmental impacts of transporting "copper rich fraction" by road

#	Categories	Normalization points per ton
1	Climate Change HH	0.002799697
2	Climate Change ED	0.000249064
3	Ozone Depletion HH	0.000000855
4	Terrestrial Acidification ED	0.000001057
5	Freshwater Eutrophication ED	0.000000019
6	Human Toxicity HH	0.000063098
7	Photochemical Oxidant Formation HH	0.000000789
8	Particulate Matter Formation HH	0.001343182
9	Terrestrial Ecotoxicity ED	0.000000491
10	Freshwater Ecotoxicity ED	0.000000004
11	Marine Ecotoxicity ED	0.000000000
12	Ionising Radiation HH	0.000001019
13	Agricultural Land Occupation ED	0.000001286
14	Urban Land Occupation ED	0.000006481
15	Natural Land Transformation ED	0.000017560
16	Mineral Resource Depletion RA	0.000003928
17	Fossil Fuel Depletion RA	0.007357451
-	**Total**	**0.011845982**

3.1.3 Final operations

When a waste fraction reaches the end of the processing chain for WEEE it is processed and incorporated in a final application which can be classified as recovery (including reuse, recycling and incineration with energy recovery) or as elimination (including incineration without energy recovery and landfill disposal).

The modelling of final operations accounted for the technical, economic and environmental aspects. Figure 3.4 presents the diagram for a technical model of a generic final operation.



RE = recovery/elimination efficiency, Cf = processing cost, Rf = recovery/elimination revenue/cost, Lf = processing and recovery/elimination environmental impact/gain, Pf = processing capacity

Figure 3.4 - Model of a generic final operation

Table 3.13 presents a (non exhaustive) list of final operations that were modelled in the research work.

Table 3.13 – Examples of final operations

Final operations	
Reuse appliances	Production of other products of/with plastics
Reuse components	Synthesis gas production
Steel mill 'traditional'	Pyrolysis
Steel mill 'special'	Particle board production
Stainless steel works	Paper/cardboard production
Cu smelter 'traditional'	Co-incineration with energy recovery
Cu smelter 'special'	Municipal waste incineration
Al smelter	Municipal waste incineration with high energy efficiency
Pb smelter	Hazardous waste incineration
Other metal smelters	Municipal waste incineration - 'special' use
CRT-glass production	Hazardous waste incineration - 'special' use
Glass production	Landfill
Production of other products of/with glass	Special landfill
Ceramic industry	Battery recycling
Concrete production	Production of oil
Road construction	Production of oil binding material
Defined construction purposes	CFC splitting to products
Other construction purposes - backfilling	CFC destruction
Filing mines - backfilling	Chemical / physical treatment as disposal process
Plastics recycling	Hg distillation - final

Notes: Included in the global model based on the technologies installed by the operators in the Portuguese infrastructure and downstream.

3.1.3.1 Technical aspects

Following the characterization of the intermediate operations, the technical aspects of the final operations were modelled accordingly using the same set of eleven material categories already presented in Table 3.2 and the formulation of the input of the input shown in Equation 3.1.

In the case of the final operations, the core technical aspect modelled was the efficiency of recovery and/or elimination characteristic of the operation and for each individual material category, enabling detailed accounting of the amounts of WEEE reused, recycled, recovered, incinerated and disposed in landfill. This was done mostly based on data from bibliographical sources and from survey with providers and operators of end-of-life technologies for reuse, recycling, recovery, incineration and landfill disposal. Ultimately, this allows the accounting of the effective reuse/recycling and recovery rates for WEEE, considering the inefficiencies throughout the entire end-of-life processing chain for WEEE.

Table 3.14 presents an example of the efficiencies of recovery/elimination for an operation of “incineration with energy recovery” of “polyurethane fraction” obtained from processing of cooling and freezing appliances. For the purpose of modelling it was considered that the final

operations do not have outputs of mass. However, because there are in fact mass outflows from final operations, it was important to have those accounted for in terms of the classification of the recovery/elimination efficiency. The models provided the detail shown in the example: for an incinerator with energy recovery there are several mass outputs, including slag which contains metals that can be recovered by special additional processing.

Table 3.14 – Efficiencies of recovery/elimination of "incineration with energy recovery" of "polyurethane fraction" in to the respective final classifications (in percentage in mass)

Material categories	Reuse	Recycling	Incineration with energy recovery	Incineration without energy recovery	Disposal in landfill	Total
Ferrous metals	0.0%	95.0%	0.0%	0.0%	5.0%	100.0%
Aluminium	0.0%	90.0%	0.0%	0.0%	10.0%	100.0%
Copper	0.0%	90.0%	0.0%	0.0%	10.0%	100.0%
Other metals	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
Plastics	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Rubber	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Textile	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Cement	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
Glass	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
Wood	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%
Other	0.0%	0.0%	100.0%	0.0%	0.0%	100.0%

Notes: Data for each material category was estimated based on incineration in municipal solid waste incinerator.

The efficiencies of recovery/elimination are defined in a matrix of eleven (from the number of categories of materials) by five (from the different classifications of the final destinations for each material), as follows.

$$RE_{n,i} \text{ (in percentage)} = \begin{pmatrix} RE1,1 & \dots & RE1,i \\ \dots & & \dots \\ REn,1 & \dots & REn,i \end{pmatrix}$$

where n = 1, …, 11 categories of materials and i = 1, …, 5 classifications of final destinations

The models of the final operations regarding the technical aspects have the following mathematical formulation shown in Equation 3.14.

Equation 3.14 – Modelling the technical aspects of final operations

$$I \times RE = Oref,$$

where I is the input of operation (in tons), RE is the matrix of efficiencies of recovery/elimination (in percentage) and Oref is the matrix of classified destinations of the operation (in tons).

The processing capacity corresponds to the amount of material that the equipment performing the final operation can process in a given time. It was modelled based on data obtained from bibliographical sources and survey with operators and end-of-life technology providers. Equation 3.15 presents the mathematical formulation of the processing capacity.

Equation 3.15 – Processing capacity

$$Pf = \frac{I}{t}$$

where Pf is the processing capacity (in tons per hour), I is the total amount of input (in tons) and t is the processing time (in hours)

The processing capacity constituted an important variable to determine the specific cost of processing.

3.1.3.2 Economic aspects

The economic aspects of a final operation include the processing cost and were modelled identically to the intermediate operations, accounting for all the investment costs, capital costs and operational costs, as previously described.

The Equation 3.16 presents the calculation of the processing cost for a final operation.

Equation 3.16 – Modelling the processing cost of final operations

$$I \times Cf = Ocf$$

where I is the total amount of the input of WEEE to the operation (in tons), Cf is the specific cost of performing the final operation to the WEEE (in euro per ton) and Ocf is the cost of processing the input of WEEE (in euro).

However, the economic aspects of a final operation also have to take in consideration the cost or revenue from having each material sent to each final destination. In the modelling, the final operations got credited with the economic value of the materials at the end of processing chain. For materials that had final destinations of reuse, recycling and sometimes incineration with energy recovery, there was a positive economic value and the respective revenue. On the other

hand, for materials that had as final destination incineration or disposal in landfill, the respective negative value and the respective cost were attributed to the final operation.

Table 3.15 presents an example of the economic value of materials per final destination for a final operation. The example shows average values that reflect the variation of prices in international markets for secondary materials obtained from the end-of-life processing of WEEE as well as other waste. The final economic values can also change for different levels of purity of the materials in each material category. Such characteristics depend of the material composition of the input and of the efficiency of separation inherent to the final operation.

Table 3.15 – Economic value of materials per final destination (in euro per ton)

Material categories	Reuse (1)	Recycling (2)	Incineration with energy recovery (3)	Incineration without energy recovery (4)	Disposal in landfill (5)
Ferrous metals	980.0	270.0	0.0	0.0	0.0
Aluminium	2310.0	2080.0	0.0	0.0	0.0
Copper	6970.0	3850.0	0.0	0.0	0.0
Other metals	103200.0	47500.0	0.0	0.0	0.0
Plastics	370.0	180.0	15.0	0.0	-40.0
Rubber	50.0	15.0	15.0	0.0	-40.0
Textile	40.0	10.0	10.0	0.0	-40.0
Cement	20.0	0.0	0.0	0.0	-40.0
Glass	50.0	10.0	0.0	0.0	-40.0
Wood	50.0	20.0	25.0	0.0	-40.0
Other	50.0	25.0	0.0	-580.0	-40.0

Notes: (1) Reuse value calculated based on average market value of used parts (average prices obtained from European Electronics Recycling Index).

(2) Recycling value calculated from average market prices for ferrous, non-ferrous and other metals material categories (London Metal Exchange, Eurofer, European Scrap Metals Index, JRC and IPTS (2007), and Ecorys et al (2008)), for plastics, rubber, textile, cement, glass, wood and other (European Electronics Recycling Index).

(3) Incineration with energy recovery values based on Manhart (2010).

(4) Incineration without energy recovery is generally only used for special treatment of hazardous materials (e.g. CFC) and the value was estimated based on data provided by the operators in the Portuguese infrastructure.

(5) Landfill disposal costs estimated based on average costs of normal landfill (for non-hazardous waste) and special landfill (for hazardous waste), based on European Commission (2012b).

The economic value of materials is defined in a matrix of eleven (from the number of categories of materials) by five (from the different classifications of the final destinations for each material), as follows.

$$Rf_{n,i} \text{ (in euro per ton)} = \begin{pmatrix} Rf1,1 & \ldots & Rf1,i \\ \ldots & & \ldots \\ Rfn,1 & \ldots & Rfn,i \end{pmatrix}$$

where n = 1, …, 11 categories of materials and i = 1, …, 5 classifications of final destinations

The models of the final operations regarding the economic aspects have the following mathematical formulation shown in Equation 3.17.

Equation 3.17 – Modelling the economic value of materials in final operations

$$I \times Rf = Orf$$

where I is the input of operation (in tons), Rf is the matrix of economic value (in euro per ton) and Orf is the matrix of the economic value per material category and per final classification (in euro).

The total economic balance of the final operation is given by the sum of the processing cost and the economic value of the materials and the end of the processing chain ($Ocf + Orf$).

3.1.3.3 Environmental aspects

The environmental aspects of the final operations were accounted for using LCA and the ReCiPe impact assessment method, identical to what was done for intermediate operations. The different final operations had the respective environmental performance modelled.

Table 3.16 presents the environmental impacts calculated for the final operation "steel mill" per ton of "iron fraction - pure" processed and recycled. The negative values indicate avoided environmental impacts and represent environmental gains.

Table 3.16 – Environmental impacts of "steel mill" of "iron fraction - pure"

#	Categories	Normalization points per ton
1	Climate Change HH	-0.1534263
2	Climate Change ED	-0.0136482
3	Ozone Depletion HH	-0.0000103
4	Terrestrial Acidification ED	-0.0000363
5	Freshwater Eutrophication ED	-0.0000050
6	Human Toxicity HH	-0.0710261
7	Photochemical Oxidant Formation HH	-0.0000148
8	Particulate Matter Formation HH	-0.1023273
9	Terrestrial Ecotoxicity ED	-0.0000559
10	Freshwater Ecotoxicity ED	-0.0000002
11	Marine Ecotoxicity ED	0.0000000
12	Ionising Radiation HH	-0.0001122
13	Agricultural Land Occupation ED	-0.0005260
14	Urban Land Occupation ED	-0.0002964
15	Natural Land Transformation ED	-0.0003469
16	Mineral Resource Depletion RA	-0.0030810
17	Fossil Fuel Depletion RA	-0.3751895
-	**Total**	**-0.1534263**

Because the results are in normalization points, it is possible to obtain the sum of the environmental impacts in the distinct impact categories according with the ReCiPe methodology. The environmental impacts of processing the input of WEEE in each final operation are given by Equation 3.18.

Equation 3.18 – Modelling the environmental impacts of final operations

$$I \times L = Ol$$

where I is the total amount of the input of WEEE to the operation (in tons), L is the specific environmental impacts of performing the operation (in normalization points per ton) and OI is the environmental impacts of processing the input of WEEE (in normalization points).

3.2 Global model of the infrastructure for end-of-life processing of WEEE

The infrastructure of end-of-life processing is constituted of different operations, from the initial stage of treatment of the whole equipment until the last stages where the material fractions obtained are in fact recovered or eliminated. A global model of the infrastructure for the end-of-life processing of WEEE was developed and includes the operators in the Portuguese infrastructure and the operations and processing techniques that each one uses to process the

WEEE, including all five different categories. The operations used by downstream operators are also modelled and their impact is reflected on the results.

The model was developed using data from several sources, including the end-of-life processing tests and the respective operators, bibliographical sources and survey with providers of end-of-life technologies for WEEE, and present different levels of quality. The experimental data obtained from the WEEE processing tests is of very high quality, considering the specific nature of the methodology and the quality control enforced by the researcher during the execution of the procedures. Also the data provided by the operators was of very high quality, mostly was verifiable with other data sources. Bibliographical data was also used mostly to prepare for and validate the field data and its quality is high. Occasionally bibliographical data was slightly out of date, not including the latest information or more recent processes and technologies. In this case, the data was complemented from surveys with technology providers. There was a question on the quality of part of such data, in particular technical and economic data that was used for commercial purposes. Such data was checked by the researcher with multiple sources of information, to ensure its credibility, and its use in the research was minimized. Regarding market data, namely material selling prices, several web based data sources were used. These are commonly used by the operators in the WEEE processing chain and are trustful, but the market prices can be volatile.

The model was developed using a modelling tool that was also developed during the research work that is easy to use and can be made accessible to many users quite easily also. Based on Excel software, the tool incorporates an interface where the user inputs the data for the individual operation, regarding the technical, economic and environmental aspects. The operation can be associated to other operations in order to form the model of a processing technique. Each operation is stored in a database and can be used in other models.

The global model developed in the research work produced technical, economic and environmental results for each operation of each processing technique used by each individual operator in the Portuguese infrastructure and downstream.

Figure 3.5 presents a schematic view of the global model.

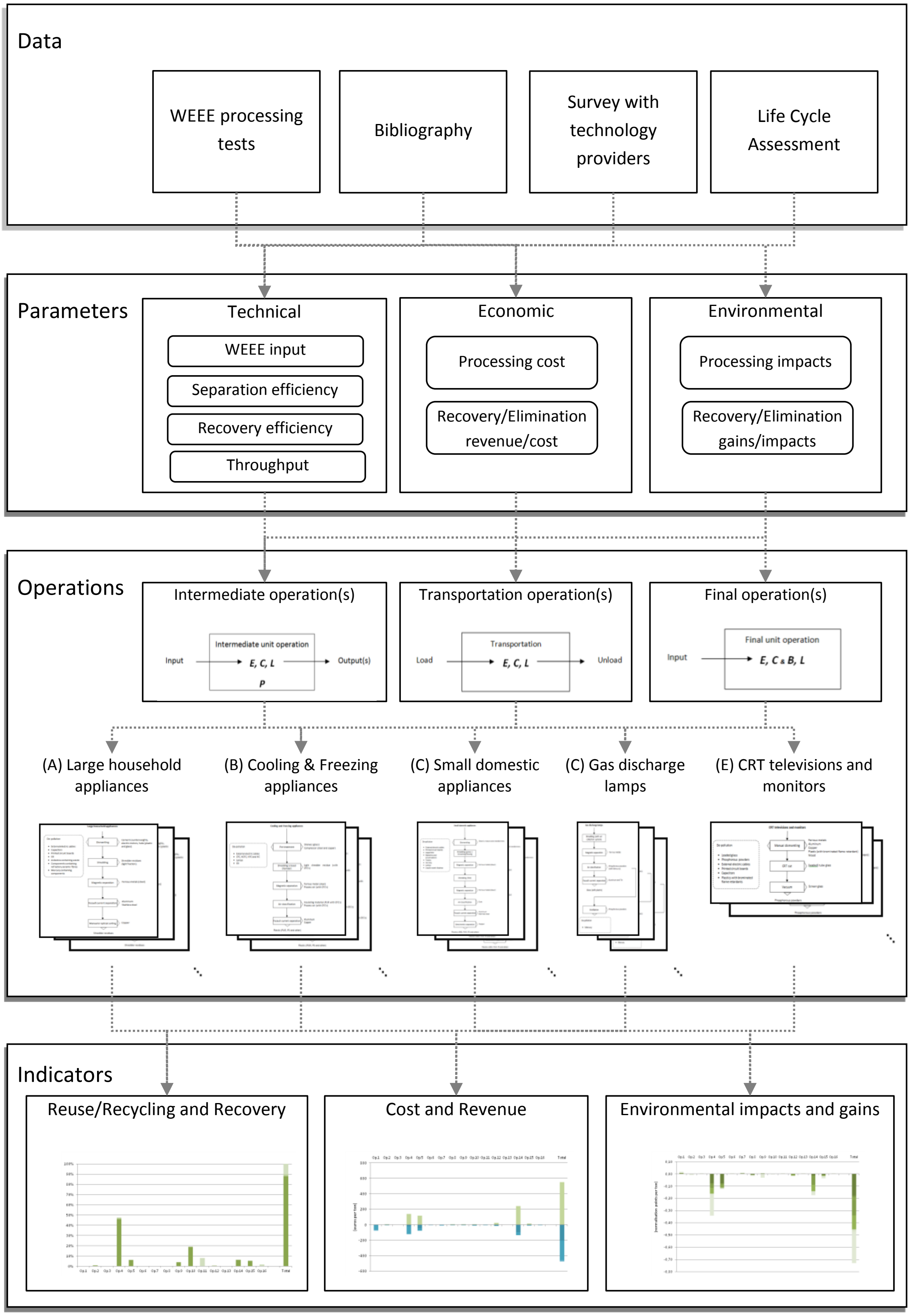


Figure 3.5 – Global model of the infrastructure for end-of-life processing of the WEEE

The model was calibrated using the data for the Portuguese infrastructure for end-of-life processing of the WEEE, and included the respective downstream operations. This allowed the model to be tested and to assess the performance of the entire chain of operations that are used to treat and recover the WEEE.

In the following section, an example of the calibration of the model is described.

3.3 Calibrating the global model

Calibrating the model was done using the technical, economic and environmental data from the end-of-life processing tests that were done on the Portuguese infrastructure and also from bibliographical sources, from a survey with providers of end-of-life technologies to process the WEEE and from Life Cycle Assessment.

The global model for the Portuguese infrastructure included all the technologies installed for each of the five categories of WEEE. It also included the operations that are performed by companies downstream of the Portuguese infrastructure in order to model the entire end-of-life processing chain.

In the context of the research work, a representative average input material composition was considered in all the models developed for the Portuguese infrastructure based on the data collected from the WEEE processing tests.

3.3.1 Technical aspects

The technical aspects constitute the basis of the models as they simulate the mass flows, which are essential to determine not only the technical performance, but also the economic and environmental performance of the end-of-life processing of the WEEE.

In this section the technical aspects and their main results are presented for each of the five categories of WEEE for the Portuguese infrastructure, including all the downstream operations until the end of the processing chain.

3.3.1.1 Large household appliances

Large household appliances typically include WEEE of large size, mostly constituted of metals and with no or small presence of hazardous substances or components. Table 3.17 presents the data from one test performed in the research work regarding the different types of equipment processed under category A (Large household appliances).

Table 3.17 – Equipment in the input material – Large household appliances

Type of equipment	% (in mass)	Unit weight (kg/unit)
Washing machines	59.9%	58.9
Dish washers	15.1%	38.1
Electric stoves	14.5%	40.0
Microwave ovens	5.3%	13.0
Tumble dryers	2.9%	25.6
Oil radiators	2.4%	14.4
Total	**100.0%**	**40.6**

Table 3.18 shows the average material composition of the input WEEE obtained in the campaign of tests in the Portuguese infrastructure that was also used in the models.

Table 3.18 – Material composition of the input material – Large household appliances

Material fractions	% (in mass)
Ferrous metals	51.5%
Aluminium	5.9%
Copper	6.6%
Other metals	1.8%
Plastics	7.1%
Rubber	3.2%
Textile	0.0%
Cement	18.8%
Glass	3.1%
Wood	1.0%
Other	1.0%
Total	**100.0%**

The operators in the Portuguese infrastructure perform processing operations on large household appliances using essentially two steps:

- The first step is based on the dismantling of the equipment, to ensure the de-pollution according with requirements of the WEEE Directive, in particular to remove hazardous substances and/or components (e.g. external electric cable, capacitors[1], printed circuit boards, oil, and other), and also to remove some specific material fractions that otherwise will not be recovered, in particular the cement counterweight, that represents approximately 19% in weight.

---

[1] *Capacitors containing PCB are common in machines sold prior to 1986 (Eugster, 2008)*

- The second step is based on shredding of the remaining carcass of the WEEE, which normally takes place in large scale shredders, primarily used to process end-of-life vehicles (ELV). The car shredders are designed to separate the ferrous metal content, which is predominant in ELV as well as in large household appliances. The shredded materials are separated into light and heavy fractions: the light fraction contains dust particles and is generally disposed of, while the heavy fraction contains metals and other materials and is separated into ferrous metals, non-ferrous metals (usually for additional separation into aluminium and copper) and the remaining shredder residue, which can contain plastics, rubber and small percentages of metals, is generally disposed of in landfills.

The entire processing chain also includes additional processes, performed by operators in Portugal and abroad, in Europe and countries outside Europe, mostly in Asia. Since the objective of the research work was to model the entire WEEE processing chain, this was achieved using data collected from the campaign of WEEE processing tests and also from literature and contact with operators and technology providers, to cover all the downstream processing until the recovery or elimination of WEEE.

As an example, Figure 3.6 presents the diagram of the first step of processing large household appliances respective of one of the operators that was tested in the campaign of WEEE processing tests. The diagram includes the processes and the output fractions that are obtained and sent to acceptors in the second level of the WEEE processing chain for further processing.

Because the WEEE processing chain is very long, only the main operation in the second step of processing large household appliances is presented here, in Figure 3.7. The remaining part of the WEEE processing chain is included in Annex II.A.

In the characterization of the WEEE processing chain it was necessary to harmonize the designations of the operations and the material fractions used by the different operators in the distinct steps of the chain. In this context, the harmonized list of designations developed by the WEEE Forum (WEEE Forum, 2008b) was used.

Regarding the operations, this list presents a specific individual designation and attributes the respective classification of the type of waste management operation (treatment, recovery or elimination) according with Commission Decision 2000/532/EC (European Commission, 2000). Based on this classification of the operations, the amount of WEEE that is reused, recycled, energy recovered, incinerated or disposed in landfill was calculated using the technical models.

Regarding the material fractions, the harmonized list by the WEEE Forum presents a specific designation and an individual classification code for each fraction, according with Commission Decision 2000/532/EC (European Commission, 2000).

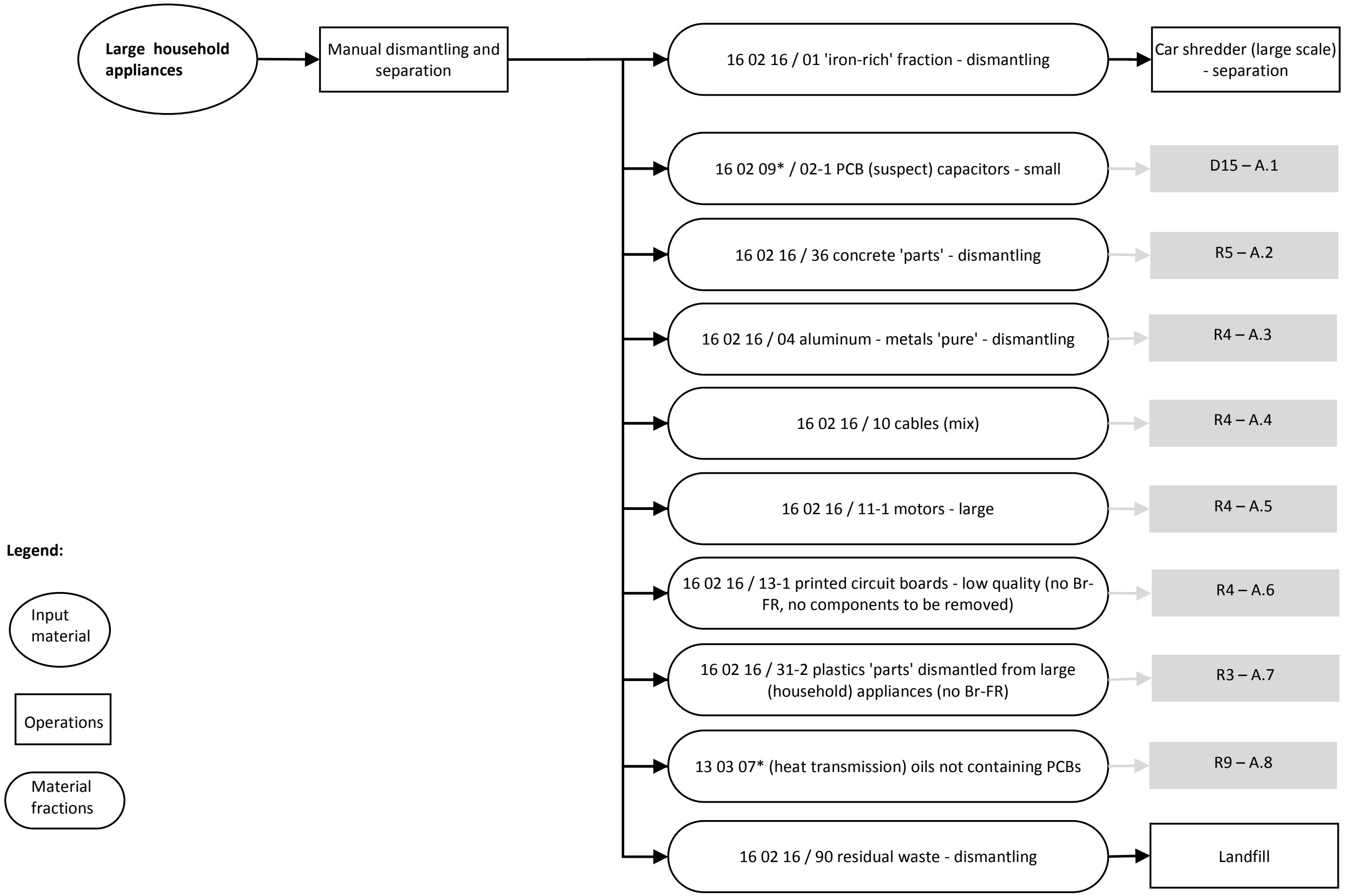


Figure 3.6 - First step of processing large household appliances (dismantling and separation)

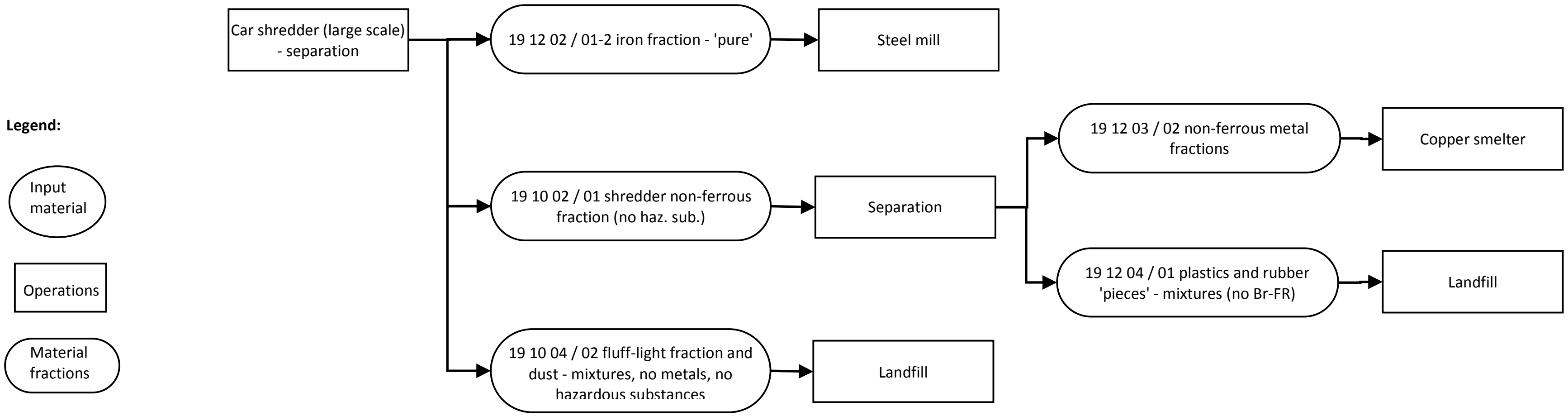


Figure 3.7 - Second step of processing large household appliances (car shredder)

Based on the amount of WEEE that is processed by each final operation and its efficiency of recovery and elimination, it was possible to determine the amount of WEEE that was reused, recycled, energy recovered, incinerated and disposed in landfill and ultimately calculate the performance in terms of rates of reuse/recycling and recovery. Figure 3.8 presents the results for one test of each individual operation per ton of WEEE (inputted to the first operation).

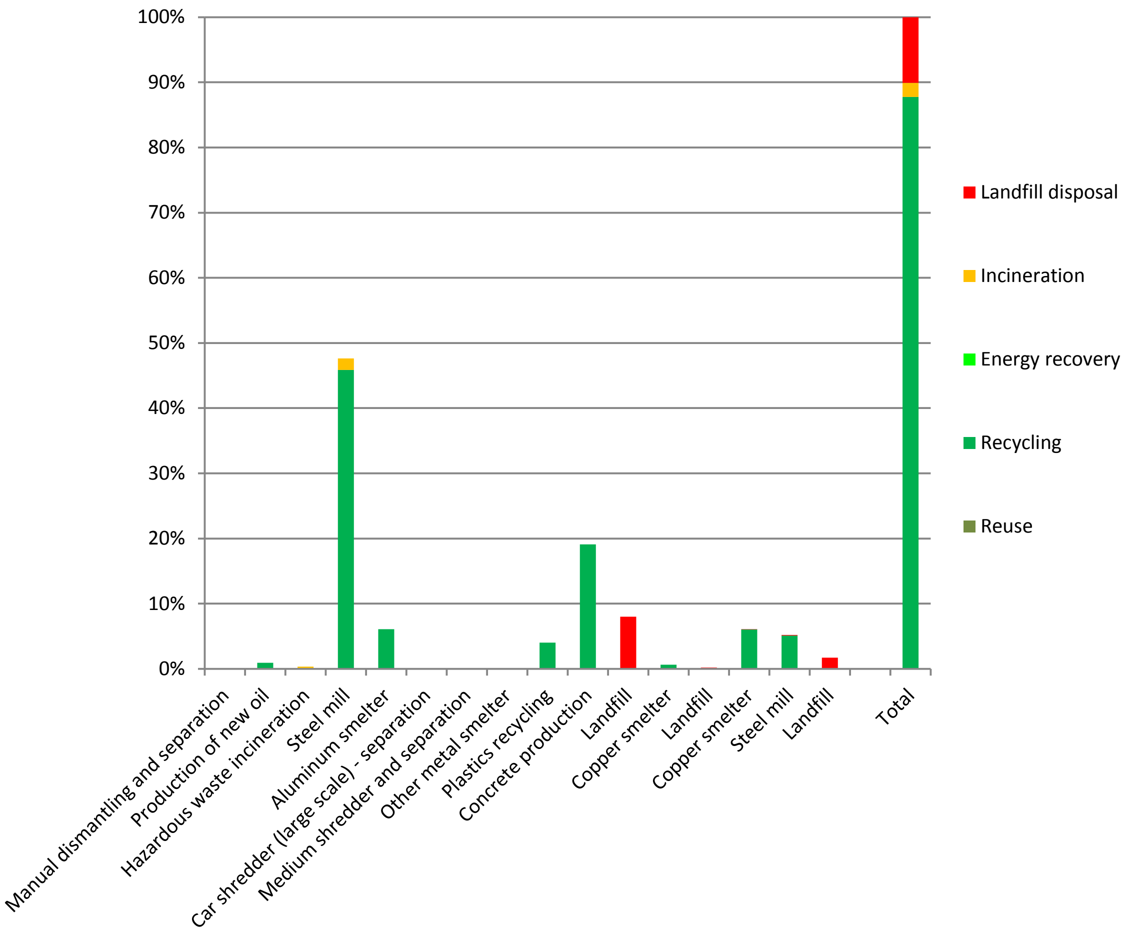


Figure 3.8 – Contribution per operation to the rates of reuse/recycling and recovery of large household appliances

The final operations are credited with the final destinations of reuse, recycling, energy recovery, incineration and landfill and so they are the contributors to the rates of reuse/recycling and recovery. For the given example, the rate of reuse and recycling of large household appliances processed in this WEEE processing chain is 87.8%, the same value as the recovery rate. Approximately 12.2% of the mass of large household appliances are eliminated by incineration and landfill disposal.

The models were developed for the alternative processing techniques used and the technologies installed by all the operators technologies in the Portuguese infrastructure, and included the operators downstream of the infrastructure. Figure 3.9 and Figure 3.10 respectively present the

performance of reuse/recycling and recovery for the 19 operators in the Portuguese infrastructure including the contribution from the downstream operations. The operators are sorted from the highest to the lowest performance. Figure 3.9 and Figure 3.10 also present the legal targets for reuse/recycling and recovery of large household appliances, respectively (European Commission, 2003b).

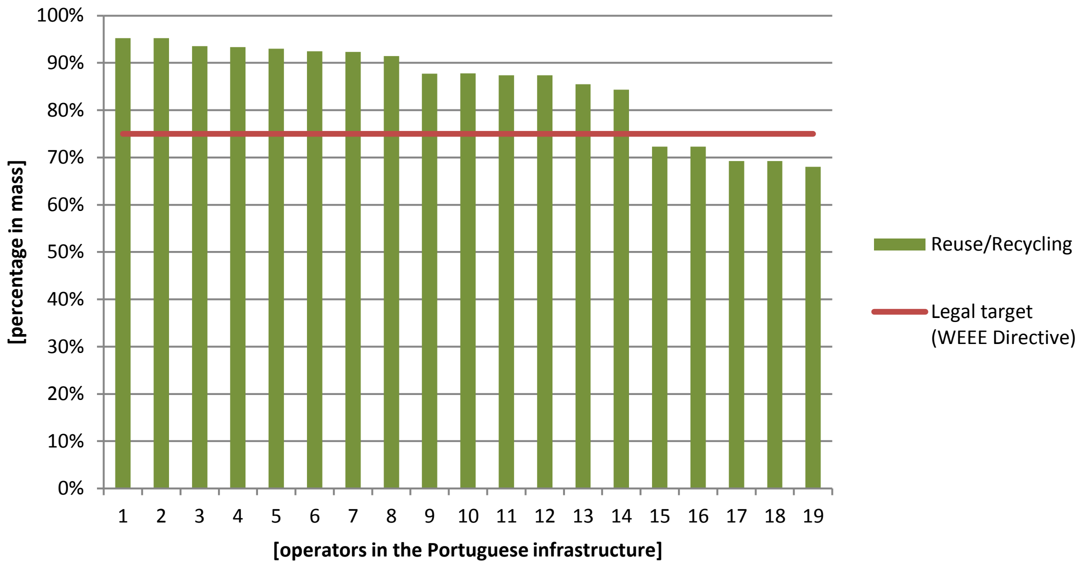


Figure 3.9 –Performance of reuse/recycling of large household appliances achieved by the operators in the Portuguese infrastructure

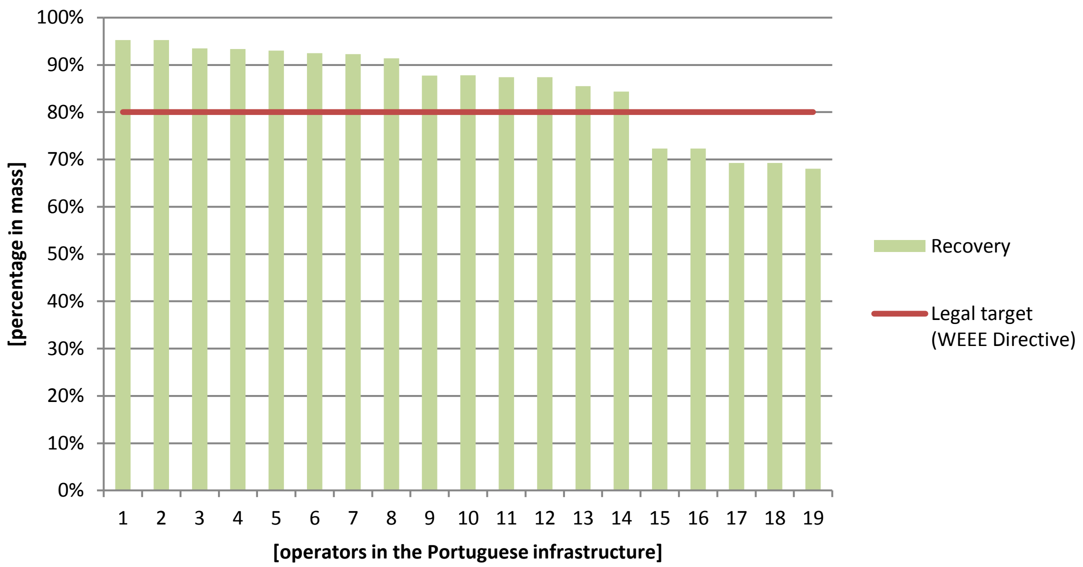


Figure 3.10 –Performance of recovery of large household appliances achieved by the operators in the Portuguese infrastructure

The models allowed to verify that the majority of operators in the Portuguese infrastructure are able to achieve performance levels for reuse/recycling and recovery of large household appliances above the minimum legal targets. On the other hand, there are still a significant number of operators performing under the minimum requirements.

3.3.1.2 Cooling and freezing appliances

Cooling and freezing appliances include refrigerators, freezers and air conditioning, and they contain substances that can potentially damage the atmosphere's ozone layer and contribute to global warming. The substances include chlorofluorocarbons, hydrochlorofluorocarbons and hydrofluorocarbons and are present in the cooling circuit, as refrigerants, and also used as blowing agents in thermal insulating polyurethane foam that fills the inside of the equipment walls.

Over the last decade, because of imposed limitations on the use of these substances (European Parliament and Council, 2000), manufacturers have replaced them with hydrocarbons, like cyclopentane refrigerants and blowing agents, that is non ozone layer depleting and has a very small potential for global warming. Table 3.19 presents some of the refrigerants and blowing agents most commonly found in WEEE from cooling and freezing appliances and their respective potential environmental impacts.

Table 3.19 – Ozone layer depletion potential and Global warming potential of refrigerants and blowing agents in Cooling and freezing appliances (PRé Consultants, 2008)

Substance	Common examples	Chemical formula	Ozone layer depletion potential (ODP)	Global warming potential (GWP)
CFC	R11	$C\,Cl_3\,F$	2400	1
HCF	R22	$CH\,Cl\,F_2$	1700	0.05
HFC	R134a	$C_2\,H_2\,F_4$	1300	-
HC	cyclopentane	C_5H_{10}	11	-

Table 3.20 shows the different types of equipment processed under category B (Cooling and freezing appliances) and the respective average presence obtained from the campaign of tests in the Portuguese infrastructure.

Table 3.20 – Equipment in the input material – Cooling and freezing appliances

Type of equipment	% (in mass)	Unit weight (kg/unit)
Fridge-Freezers (180 to 350L)	86.7%	49.0
Freezers (<500L)	9.0%	45.0
Refrigerators (<180L)	4.3%	37.0
Total	**100.0%**	**47.9**

Table 3.21 presents the respective average material composition of cooling and freezing appliances that was used to characterize the input WEEE in the models.

Table 3.21 – Material composition of the input material – Cooling and freezing appliances

Material fractions	% (in mass)
Ferrous metals	51.8%
Aluminium	3.3%
Copper	8.9%
Other metals	0.0%
Plastics	33.7%
Rubber	1.5%
Textile	0.0%
Cement	0.0%
Glass	0.5%
Wood	0.0%
Other (incl. CFC. HCFC. etc.)	0.3%
Total	**100.0%**

The processing of cooling and freezing appliances is primarily directed at the separation and capture of the hazardous substances in the refrigerant and blowing agent, as required by the WEEE Directive. Additionally, the processing is intended to separate the different fractions according with the material content in cooling and freezing appliances, namely to separate the ferrous metals, the non-ferrous metals (aluminium and copper) and plastic, so they can be recycled and/or recovered.

The treatment process is performed by fully dedicated technologies and it consists of main two stages, as follows:

- Step 1 includes the extraction of the refrigerant and oil mixture from the cooling circuit of the equipment, which normally involves perforating the compressor(s) or puncturing the tubing with specific tools attached to a vacuum system. At this stage there is also the manual dismantling of loose parts inside the cooling and freezing appliances (e.g. glass and plastic shelves), the cutting of the external electric cable, and the removal of the emptied compressors.
- Step 2 includes shredding the carcass of equipment in a close chamber with controlled inert atmosphere (by injection of nitrogen) to prevent explosions from the release of HC substances (originating from cyclopentane cooling and freezing appliances), and collect the blowing agent substances (CFC, HCFC, HFC and HC). This is followed by the separation of the ferrous metals fraction, the light fraction including the polyurethane isolating foam, and the non-ferrous metals and the plastic fractions.

Part of the blowing agent can still remain in the PUR foam, for which there are technologies that compress the fraction, expel the blowing agent and then form pellets of polyurethane.

The gaseous substances extracted in Step 1 and Step 2 of processing are usually collected and stored in specifically designed pressure bottles, to be sent for high temperature incineration, required to destroy the substances and prevent the formation of new hazardous substances. Such incineration facilities do not exist in Portugal, and so the WEEE treatment operators ship this fraction abroad, for final processing.

Alternatively, there are technologies that allow the thermal destruction *in situ*, just after Step 2, in what is designated as Step 3 of processing. Such technologies are not installed in Portugal and there are only a few installations in Europe that operate them.

The operators that process cooling and freezing appliances in the Portuguese infrastructure were modelled. They have similar technologies installed, which are characterized by the diagram in Figure 3.11. The subsequent steps of the WEEE processing chain are presented in Annex II.B.

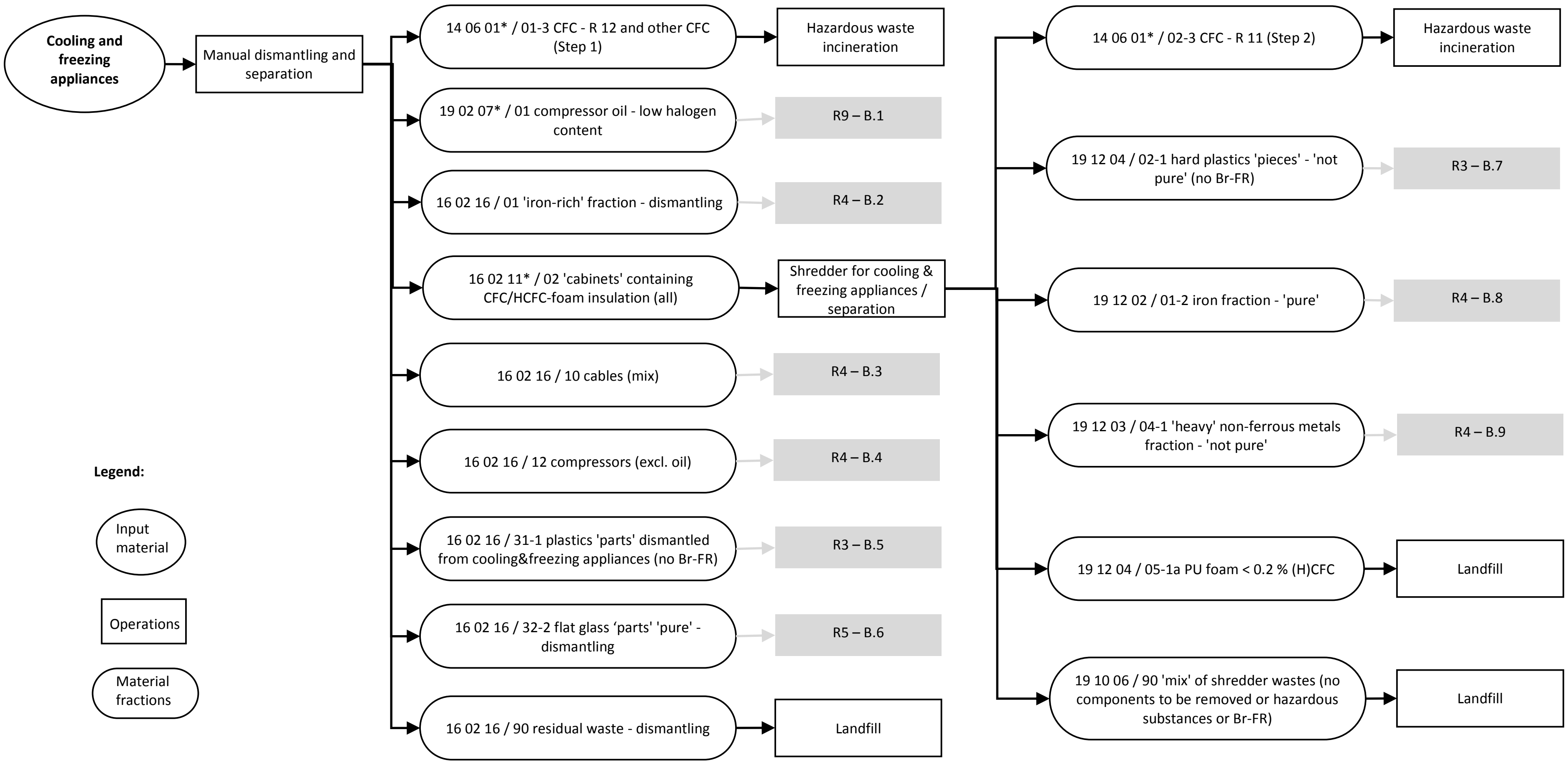


Figure 3.11 – Step 1 and Step 2 of processing cooling and freezing appliances

Figure 3.12 presents the results for one technology obtained in one test, and the respective contribution of each operation to the reuse/recycling and recovery rates.

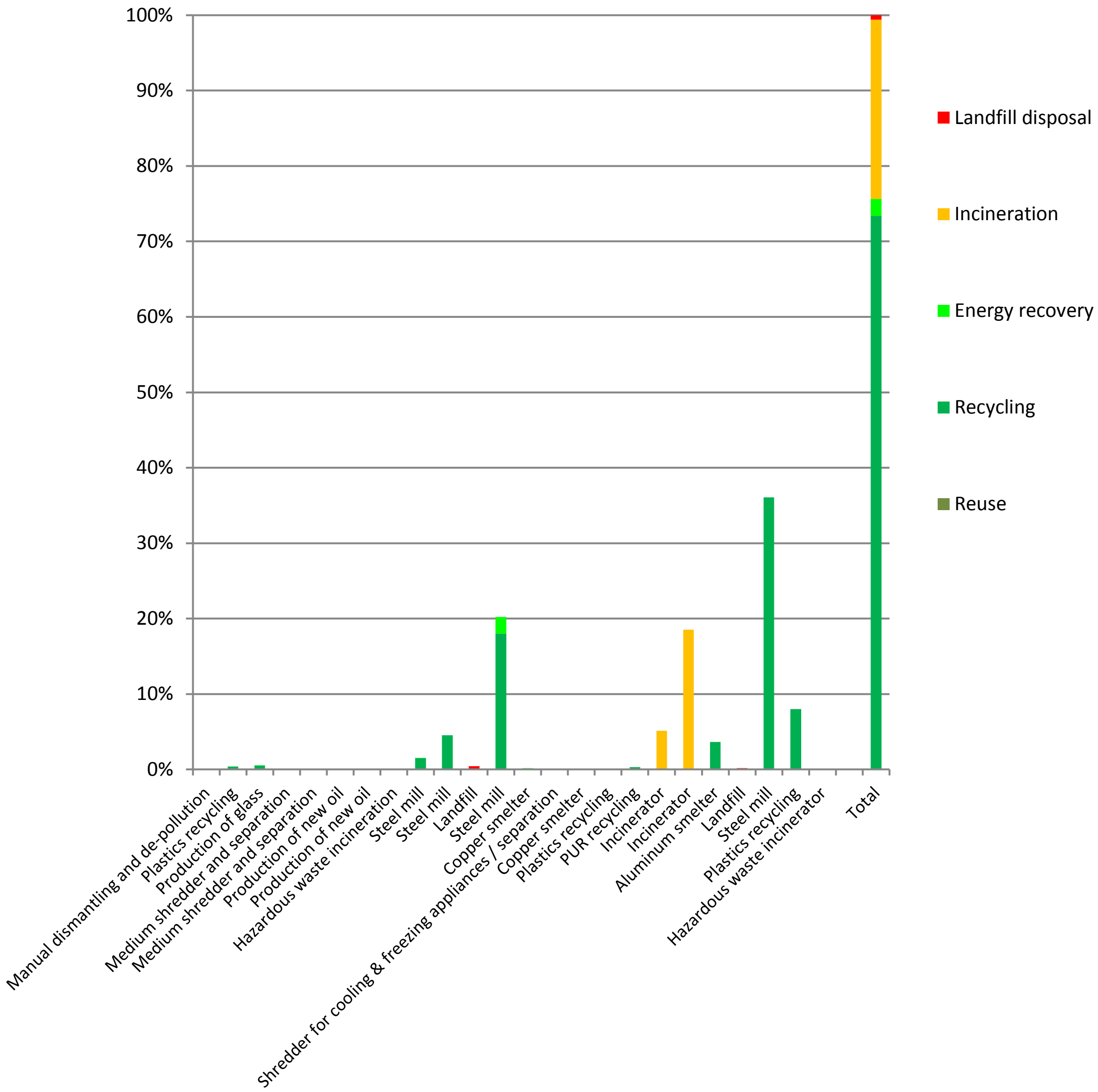


Figure 3.12 – Contribution per operation to the rates of reuse/recycling and recovery of cooling and freezing appliances

The models were developed for the technologies installed in the Portuguese infrastructure including the downstream operations, as well as for the different processing techniques used by the operators. Figure 3.13 and Figure 3.14 respectively present the performance of reuse/recycling and recovery for the 3 operators in the Portuguese infrastructure, including the contribution from the downstream operations, and compares it with the legal targets (European Commission, 2003b). The operators are sorted from the highest to the lowest performance.

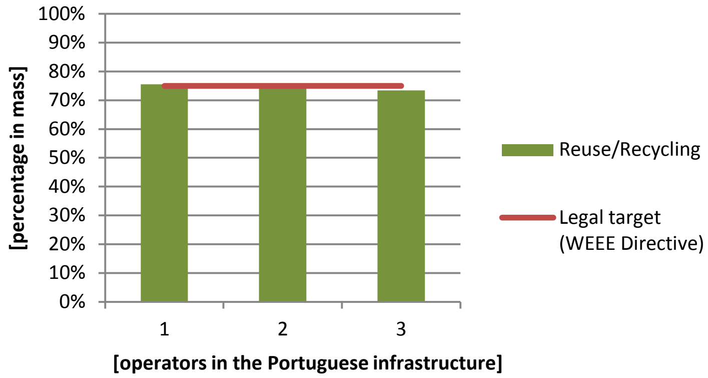


Figure 3.13 –Performance of reuse/recycling of cooling and freezing appliances achieved by the operators in the Portuguese infrastructure

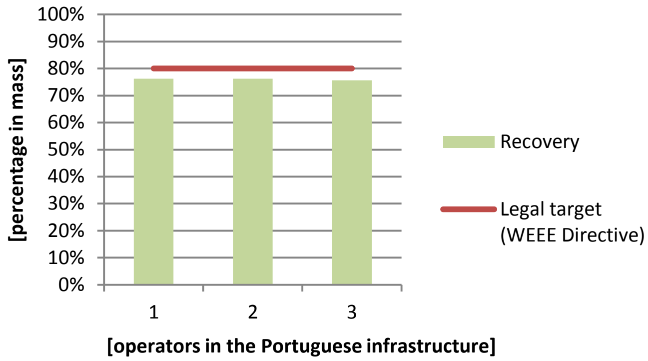


Figure 3.14 –Performance of recovery of cooling and freezing appliances achieved by the operators in the Portuguese infrastructure

The operators in the Portuguese infrastructure are barely able to achieve the performance level required to fulfil the minimum targets of reuse/recycling, and regarding the recovery they are all under the legal targets.

3.3.1.3 Small domestic appliances

Small domestic appliances are composed of equipment from many different legal categories, although they share some characteristics, such as the small size and relatively low hazardousness. With the exception of legal category 1 – large household appliances, all the remaining 9 legal categories are present in small domestic appliances. Table 3.22 shows the different types of equipment that are on average processed under category C, as a result of the tests performed in the Portuguese infrastructure.

Table 3.22 – Equipment in the input material – Small domestic appliances

Type of equipment	% (in mass)	Unit weight (kg/unit)
Small household appliances	33.0%	2.2
IT and telecommunications equipment	50.7%	3.1
Consumer equipment	12.0%	2.0
Lighting equipment (excluding lamps)	1.6%	1.5
Electrical and electronic tools	1.5%	2.8
Toys. leisure and sports equipment	0.3%	1.2
Medical devices	0.3%	1.5
Monitoring and control instruments	0.2%	2.4
Automatic dispensers	0.5%	3.3
Total	**100.0%**	**2.6**

Table 3.23 presents the respective average material composition of small domestic appliances that was used to characterize the input WEEE in the models.

Table 3.23 – Material composition of the input material – Small domestic appliances

Material fractions	% (in mass)
Ferrous metals	41.5%
Aluminium	10.0%
Copper	6.1%
Other metals	1.3%
Plastics	33.3%
Rubber	4.6%
Textile	0.0%
Cement	0.0%
Glass	1.2%
Wood	0.1%
Other	1.9%
Total	**100.0%**

Small domestic appliances are one of the most heterogeneous WEEE treatment categories, with different types of equipment and different material contents. Consequently, there is a wide range of technologies to treat such WEEE, which rely on dismantling, mechanical processing or combinations of both.

- Manual dismantling is common to respond to de-pollution requirements of the WEEE Directive, by ensuring the removal of hazardous components and/or substances from

small domestic appliances, among other, the external electric cables, capacitors, batteries and accumulators, printed circuit boards, ink lints and toner cartridges. This process can be the preparation for a next step of mechanical processing, or it can also be used to separate material fractions intended for reuse, recycling or recovery. It is commonly used to separate valuable material fractions that would be lost if processed mechanically (e.g. microchips and printed circuit boards from computers).

- Mechanical processing may include shredding the small domestic appliances to medium sized particles (in the range of centimetres) followed by automated separation of ferrous metals, non-ferrous metals (aluminium and copper) and plastics. It may also include light breaking up of the small domestic appliances, to gain access to their inside, followed by manual separation (handpicking) of hazardous components and eventually also the separation of material fractions for recovery.
- Several combinations of manual and mechanical processing can be used, to optimize the de-pollution and material recovery of small domestic appliances. These usually depend on the balance between the labour costs and the value of the material content in small domestic appliances.

In Portugal, WEEE treatment operators apply dismantling in the processing of small domestic appliances, to ensure both the legally mandatory removal of hazardous components and/or substances (European Commission, 2003b) and also to separate the material fractions for recovery. Since 2011, there are also mechanical processing technologies installed by operators in the Portuguese infrastructure, used for the same purposes of de-pollution and material separation for recovery. These technologies have been tested and modelled as part of the research work.

As an example, Figure 3.15 shows the diagram of processing small domestic appliances using a combination of manual and mechanical processes. The diagram is limited to the first steps of WEEE processing and the remaining stages are included in Annex II.C.

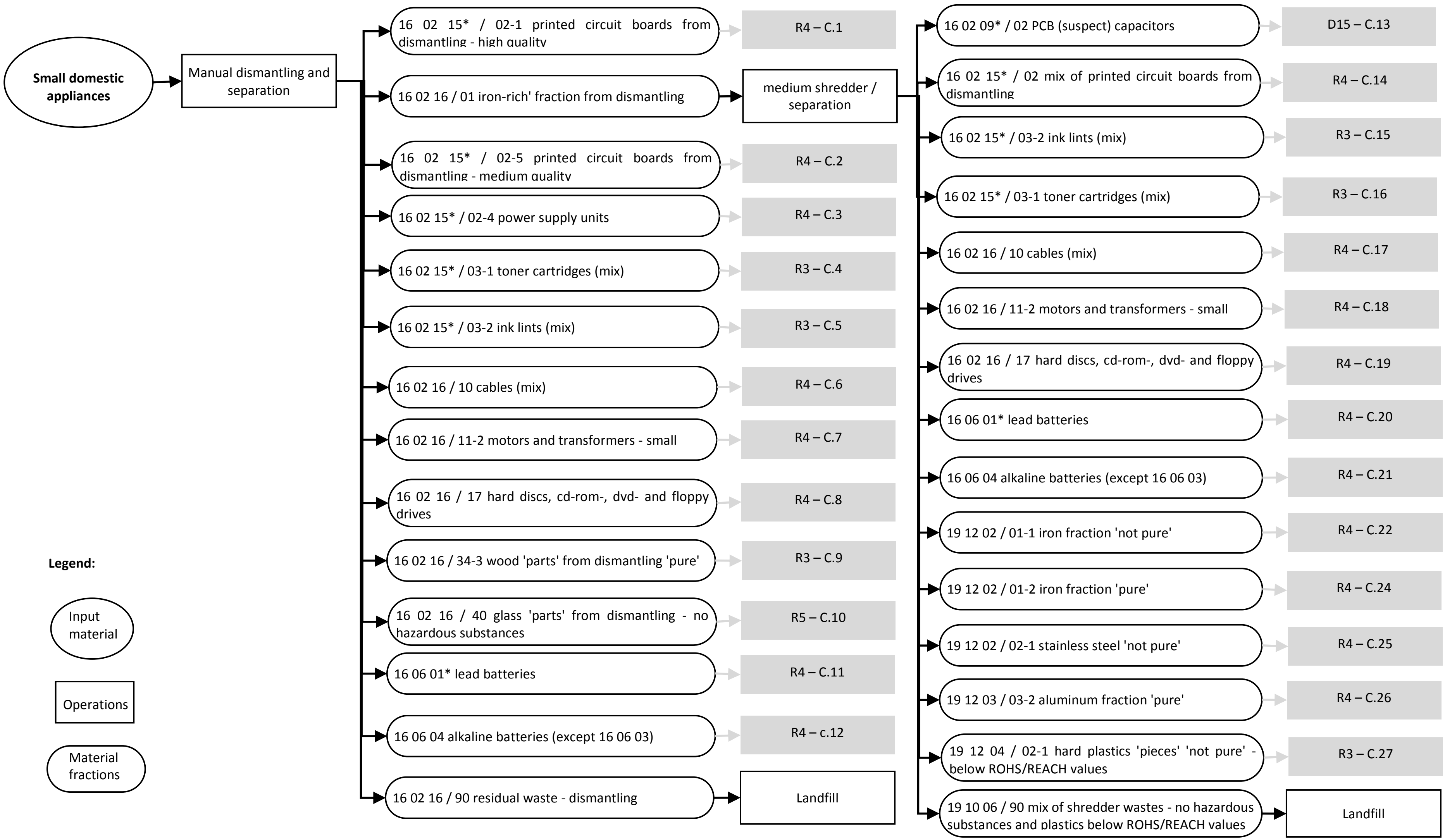


Figure 3.15 – Diagram of processing small domestic appliances

Figure 3.16 presents the results from one test, for one technology, and the contribution per operation to the reuse/recycling and recovery performance, considering 1 ton of input material. For the given example, the rate of reuse and recycling and the rate of recovery of small domestic appliances processed are both equal to 74.8%. Approximately 25.2% of the mass of small domestic appliances are eliminated by incineration and landfill disposal.

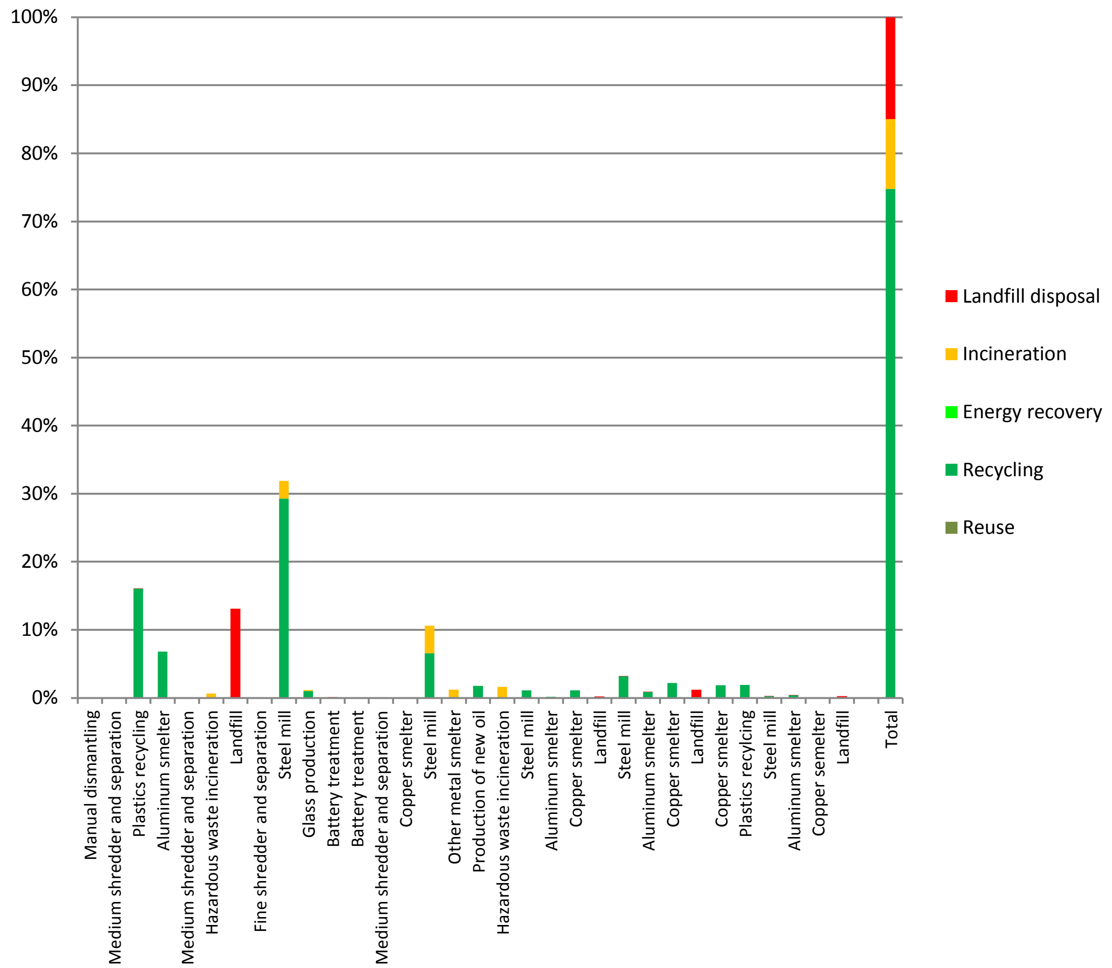


Figure 3.16 – Contribution per operation to the rates of reuse/recycling and recovery of small domestic appliances

Figure 3.17 and Figure 3.18 respectively present the performance levels of reuse/recycling and recovery for each of the operators in the Portuguese infrastructure, including the downstream operations. The performance levels are sorted from the highest to the lowest and compared to the minimum legal target (European Commission, 2003b).

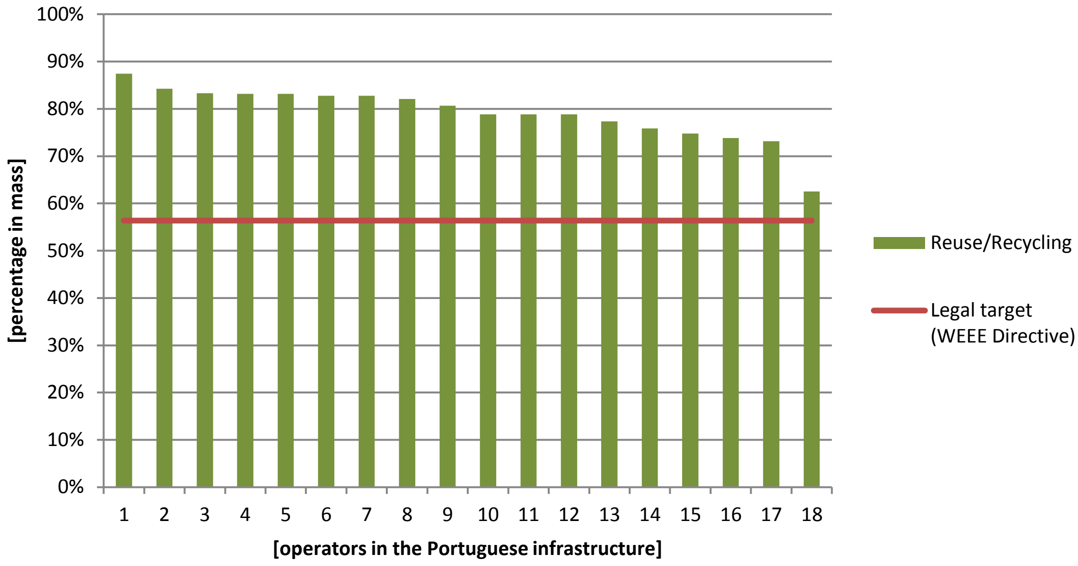


Figure 3.17 –Performance of reuse/recycling of small domestic appliances achieved by the operators in the Portuguese infrastructure

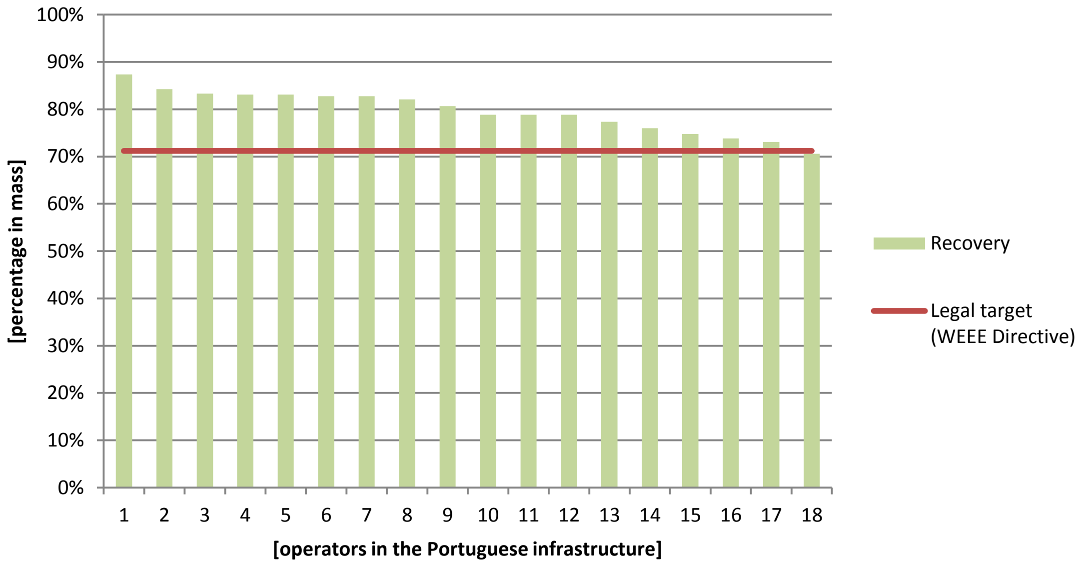


Figure 3.18 –Performance of recovery of small domestic appliances achieved by the operators in the Portuguese infrastructure

It is possible to conclude that all the operators in the Portuguese infrastructure are able to achieve the performance level required to fulfil the minimum targets of reuse/recycling and recovery.

3.3.1.4 Gas discharge lamps

The present WEEE treatment category comprehends lamps, including fluorescent tubular, compact gas discharge, high intensity discharge and low pressure Sodium lamps. The incandescent lamps (i.e. filament light bulbs) are not part of the scope of the WEEE Directive and thus are not included in the WEEE treatment category.

The technologies used to process the different types of lamps differ. However, the overwhelming majority of the WEEE treatment category is composed of fluorescent tubular lamps, more than 83% in weight (United Nations University, 2007). Table 3.24 presents the typical characteristics of the equipment in the WEEE category D (Gas discharge lamps) obtained from the campaign of tests in the Portuguese infrastructure.

Table 3.24 – Equipment in the input material – Gas discharge lamps

Type of equipment	% (in mass)	Unit weight (kg/unit)
Fluorescent tubular lamps – large	96.1%	0.197
Fluorescent tubular lamps – medium	3.9%	0.160
Total	**100%**	**-**

Table 3.25 shows the respective average material composition of gas discharge lamps that was used to characterize the input WEEE in the models.

Table 3.25 – Material composition of the input material – Gas discharge lamps

Material fractions	% (in mass)
Ferrous metals	1.6%
Aluminium	0.6%
Copper	0.1%
Other metals (incl. mercury)	<0.1%
Plastics	5.5%
Rubber	0.0%
Textile	0.0%
Cement	0.0%
Glass	90.5%
Wood	0.0%
Other	1.6%
Total	**100.0%**

Lamps are characterized by a very high percentage of glass, that can be recycled, and also by the presence of mercury, a metal that can affect human health and the environment and has to be

removed separately according with legal de-pollution requirements (European Commission, 2003b).

In this context, the processing of gas discharge lamps is focused on the removal of the mercury content and on the separation of the glass, metals and plastic materials and the phosphorous powders. On average, the recycling alone of the glass content is enough to achieve the legal target on reuse/recycling of 80% (European Commission, 2003b).

The most common processing technologies are characterized by shredding of the lamps. Less common technologies cut off the lamps extremities, removing the respective metal terminals. In either technology, there is extraction and concentration of the phosphorous powders in which the mercury is absorbed. In order to achieve an efficient extraction of the phosphorous powders and avoid any loss of mercury that can contaminate other output material fractions, the most recent technologies use an air extraction and classification system throughout the processing line. This greatly reduces the presence of phosphorous powders in the plastics, metals and especially the glass fractions.

After shredding or cutting off the extremities, the ferrous metals are separated by magnetic separation, non-ferrous metals by eddy current separation, and the remaining glass and plastic fractions. This phosphorous powders containing mercury are subjected to distillation to separate this metal content.

The mercury has been recycled for many years while the phosphorous powders used to be stored or disposed in landfills until recently. Significant attention has been given to these phosphorous powders, as there is growing international disputes by European countries, the United States of America and Chine to access rare earths elements[2]. These elements are key to manufacture high tech electronic products and electric components of motors used in electric vehicles and generators in wind turbines. More than 90% of the world's production of rare earth elements belongs to China (Humphries, 2012) and since the end of 2011, when the country imposed heavy restrictions on exports, the price of rare earths in the international market increased significantly (Iamgold, 2012). This left manufacturers and governments outside China to start looking into the possible alternative sources for rare earth elements, among which the recycling of phosphorous powders from lamps, where rare earth elements can be found (Schuler et al., 2011).

Figure 3.19 shows one example of a diagram representing the operations performed in the end-of-life processing of WEEE from treatment category D (Gas discharge lamps). The remaining stages of the WEEE processing chain are presented in Annex II.D.

[2] ***Rare earth elements*** *or* ***rare earth metals*** *are a set of seventeen chemical elements in the periodic table, specifically the fifteen lanthanides plus scandium and yttrium.* Because *of their geochemical properties, rare earth elements are typically dispersed and not often found in concentrated and economically exploitable forms.*

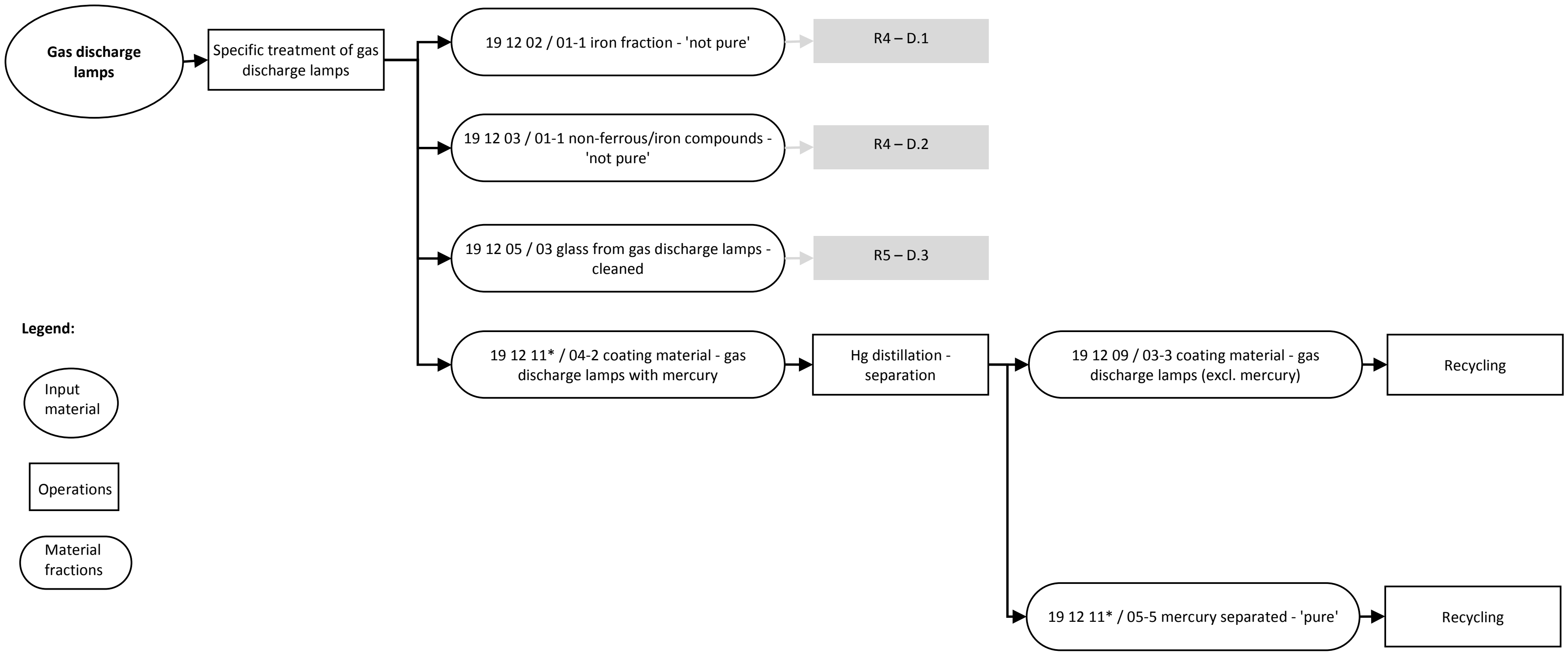


Figure 3.19 – Diagram of processing gas discharge lamps

Figure 3.20 presents the results of one test for one technology and the contribution per operation to the reuse/recycling and recovery performance of processing 1 ton. The highest contribution comes from the final operation associated with the recycling of glass which is the most representative material present in gas discharge lamps.

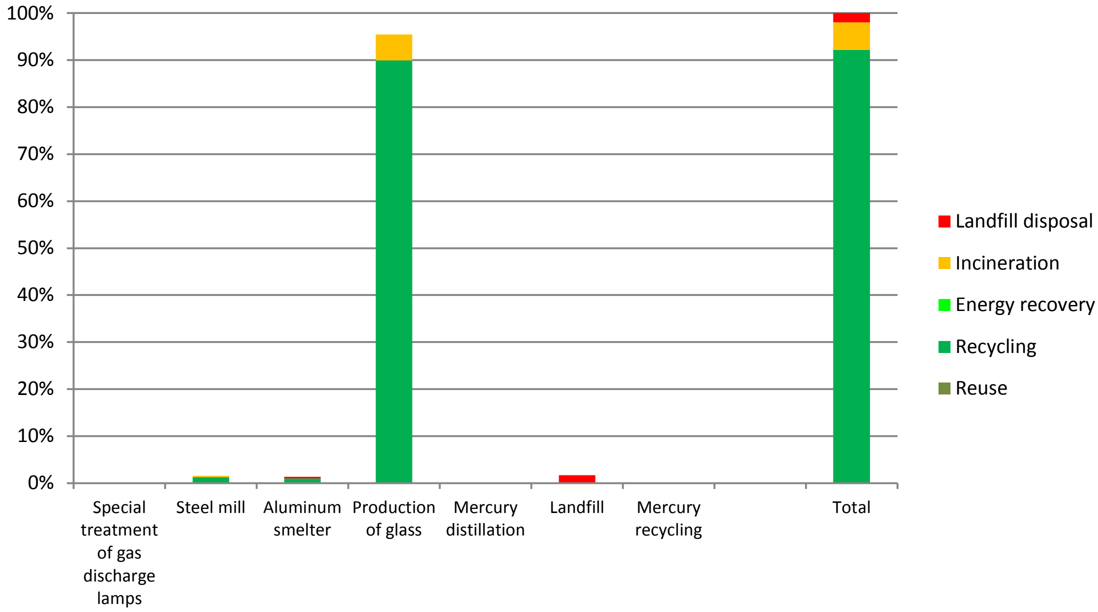


Figure 3.20 – Contribution per operation to the rates of reuse/recycling and recovery of gas discharge lamps

Figure 3.21 and Figure 3.22 respectively present the total performance of reuse/recycling and recovery for the operators in the Portuguese infrastructure, including the downstream operations. The performance is compared to the legally binding targets (European Commission, 2003b).

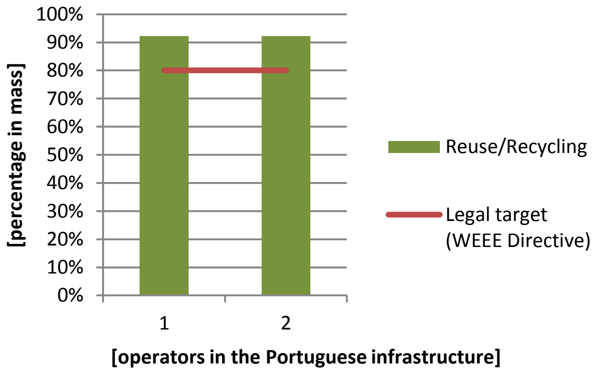


Figure 3.21 –Performance of reuse/recycling of gas discharge lamps achieved by the operators in the Portuguese infrastructure

The rate of reuse/recycling and the rate of recovery are identical; considering the material composition of gas discharge lamps, there is hardly any material that can be incinerated to produce energy, and so energy recovery is null.

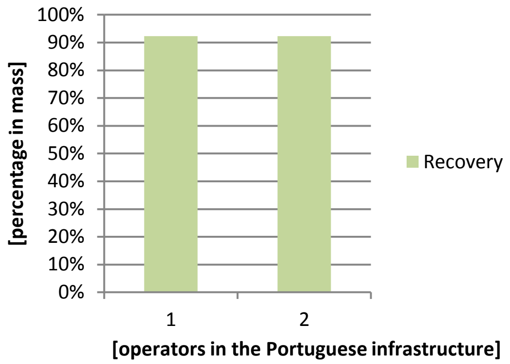


Figure 3.22 –Performance of recovery of gas discharge lamps achieved by the operators in the Portuguese infrastructure

The WEEE processing chains of which the operators in the Portuguese infrastructure are part of achieve high performance levels in the reuse and recycling of gas discharge lamps, and fulfil the respective legal targets. Recovery performance level is also high, despite the absence of any specific legal targets.

3.3.1.5 CRT televisions and monitors

The present WEEE treatment category is restricted to very specific types of equipment, namely televisions and monitors with cathode ray tube display technology. Table 3.26 presents the typical composition of WEEE in category E (CRT televisions and monitors) as a result of the campaign of tests in the Portuguese infrastructure.

Table 3.26 – Equipment in the input material – CRT televisions and monitors

Type of equipment	% (in mass)	Unit weight (kg/unit)
Television sets	66.1%	17.1
Monitors	33.9%	13.3
Total	**100.0%**	**15.6**

CRT's are the main components in the equipment, they´re essentially made of glass, including leaded glass, which has to be removed separately according with de-pollution requirements by the WEEE Directive (European Commission, 2003b). CRT televisions and monitors are basically constituted by glass, plastics and metals, and they also include phosphorous powder coatings which are hazardous substances and also have to be extracted separately according with legal

requirements (European Commission, 2003b). Table 3.27 presents the respective average material composition of CRT televisions and monitors that was used to characterize the input WEEE in the models.

Table 3.27 – Material composition of the input material – CRT televisions and monitors

Material fractions	**% (in mass)**
Ferrous metals	13.2%
Aluminium	1.0%
Copper	3.8%
Other metals (incl. mercury)	0.6%
Plastics	26.6%
Rubber	1.5%
Textile	0.0%
Cement	0.0%
Glass	50.9%
Wood	2.2%
Other	0.2%
Total	**100.0%**

The processing of CRT televisions and monitors is designed to ensure the separation of the CRT tube and the removal of the hazardous leaded glass contained in it, as well as the separation of the phosphorous powders which are adhered in a layer on the inside face of the screen. Simultaneously, the processing of CRT televisions and monitors intends to separate material fractions that can be recovered.

The treatment of CRT televisions and monitors is very specific and the existing technologies are exclusively dedicated to such WEEE. The processing includes two fundamental steps, as follows:

- Step 1 is characterized by the dismantling of televisions and monitors. In this operation the external covering is removed to gain access to the inside of the equipment and the whole CRT is separated. Other material fractions are also separated according with de-pollution requirements, including external electric cables and printed circuit boards. Other material fractions are separated in order to be recovered, such as copper wiring, power supply units, plastic casing, etc.
- Step 2 is dedicated to processing the CRT. It can be done by one of two technologies: a) CRT cutting (e.g. hot wire and rapid cooling technique, laser cutting, diamond cutting wire, diamond cutting saw or water jet cutting) followed by manual separation of components or, alternatively, b) CRT crushing/shredding followed by automated sorting of components.

Step 2b) normally presents higher throughput than Step 2a) but it comparatively requires more significant investments in processing equipment and higher amounts of input material to be

economically viable (United Nations University, 2007). Operators in the Portuguese infrastructure use Step 2a) processing.

The operations and respective output fractions form the processing of CRT televisions and monitors are presented in the diagram in . The remaining stages of processing are included in Annex II.E.

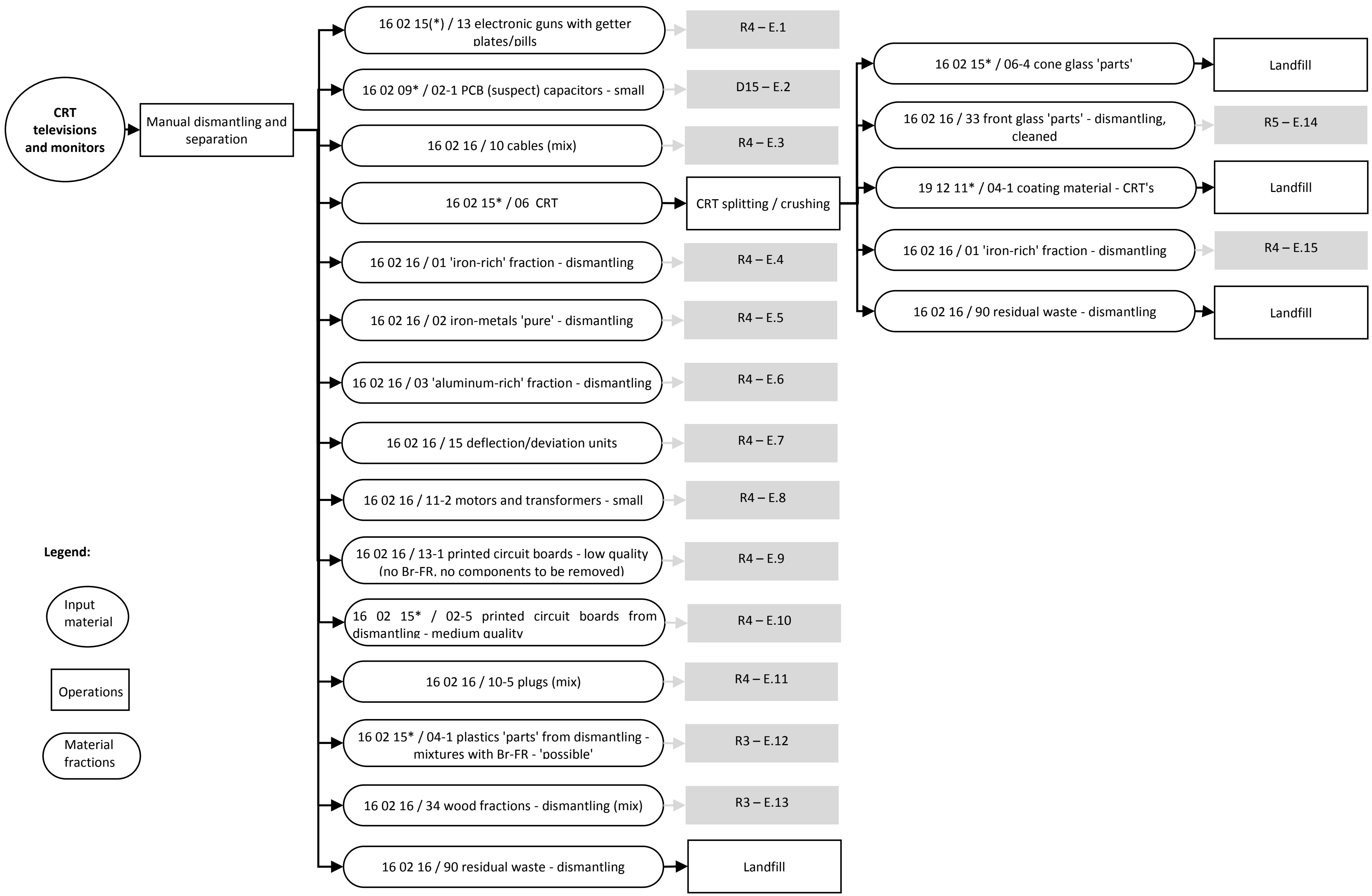


Figure 3.23 – Diagram of processing CRT televisions and monitors

Figure 3.24 presents the results for one technology, obtained from one test, and the contribution per operation to the reuse/recycling and recovery performance. For the given example, the rate of reuse and recycling and the rate of recovery of gas discharge lamps processed in this WEEE processing chain are equal to 65.2%. A significant part of the mass of gas discharge lamps, approximately 34.8% is eliminated by incineration and landfill disposal.

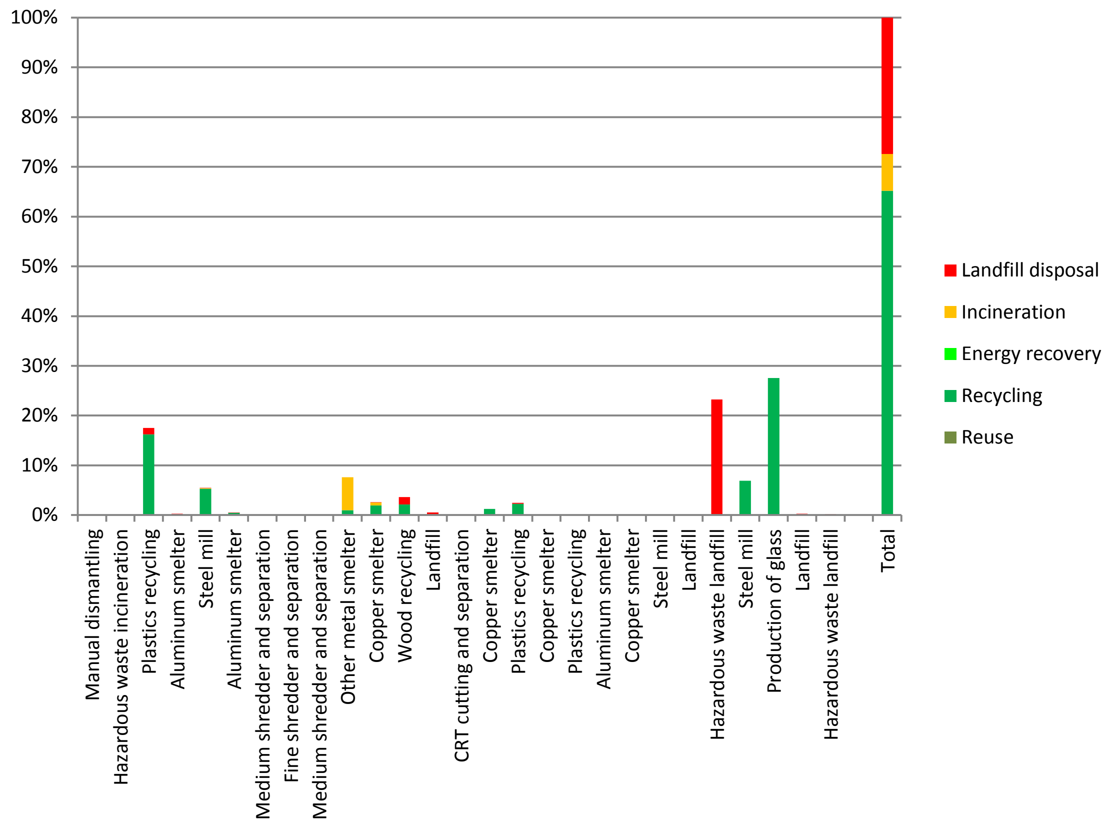


Figure 3.24 – Contribution per operation to the rates of reuse/recycling and recovery of CRT televisions and monitors

The models were developed for the operators in the Portuguese infrastructure, including the operations downstream of this. Figure 3.25 and Figure 3.26 respectively present the total performance of reuse/recycling and recovery for the operators in the Portuguese infrastructure. The operators levels are sorted from the highest to the lowest performance and the respective levels are compared to the legal targets (European Commission, 2003b).

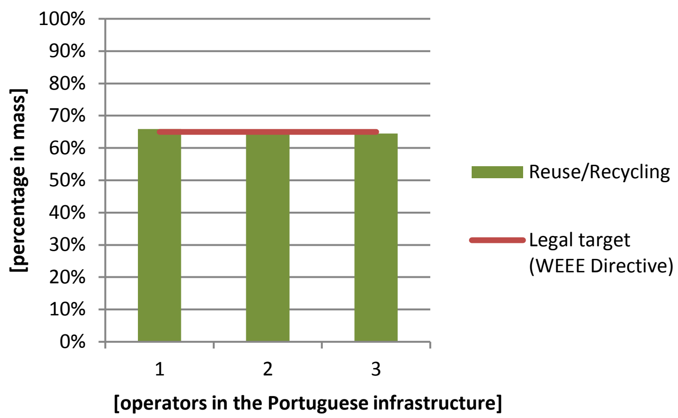


Figure 3.25 –Performance of reuse/recycling of CRT televisions and monitors achieved by the operators in the Portuguese infrastructure

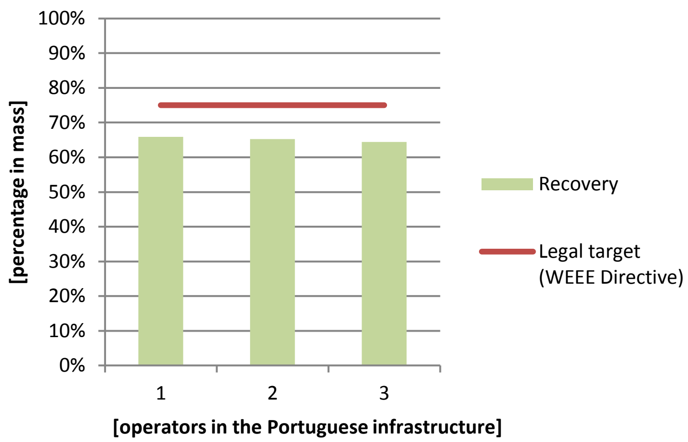


Figure 3.26 –Performance of recovery of CRT televisions and monitors achieved by the operators in the Portuguese infrastructure

The results indicate that the operators in the Portuguese infrastructure are able to achieve the performance level required to fulfil the minimum targets of reuse/recycling, but are unable to fulfil the targets for recovery.

3.3.2 Economic aspects

The models were developed and the economic aspects were included to assess the economic balance of the end-of-life processing of the WEEE considering each of the five categories of WEEE, the operations performed and the technologies installed in the Portuguese infrastructure including the downstream operations. The models were developed based on the

characterization data provided by the campaign of WEEE processing tests and also from bibliographical sources and the survey with providers of end-of-life technologies.

3.3.2.1 Large household appliances

Each operation in the end-of-life processing chain for large household appliances was modelled and the cost and revenue accounted to determine the economic balance.

Considering the example of the technical aspects of the end-of-life processing of large household appliances already referred, Figure 3.27 presents the economic contributions of each operation for the given operator and the installed technology. The outcome of the total economic balance for large household appliances processed is a positive value of 75.0 euros per ton of input WEEE.

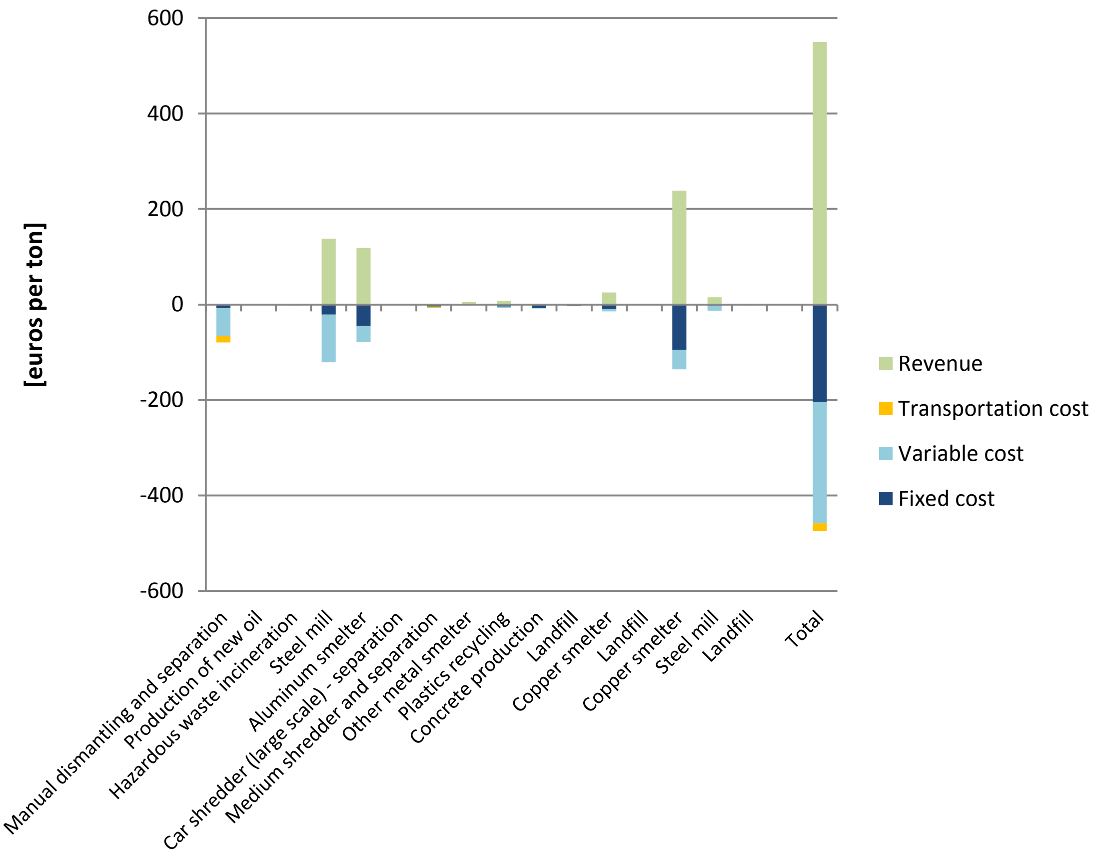


Figure 3.27 – Contribution per operation to the economic balance of the processing of large household appliances

The operations, the processing techniques and the technologies installed in the Portuguese infrastructure, including the respective downstream ones, were modelled and the economic performance was determined. Figure 3.28 shows the total economic balance for end-of-life

processing of large household appliances achieved by the operators in the Portuguese infrastructure. The operators were sorted from the highest to the lowest economic performance.

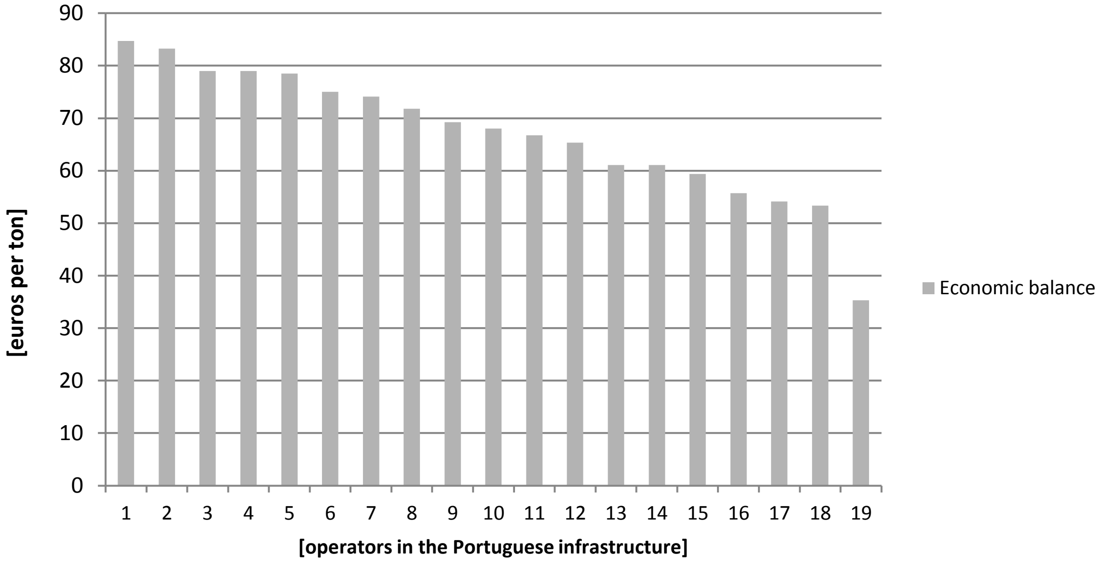


Figure 3.28 –Economic performance of large household appliances achieved by the operators in the Portuguese infrastructure

The results indicate that the end-of-life processing of large household appliances has a positive economic balance, with revenue surpassing the cost in all operators in the Portuguese infrastructure. There values range between 35.3 and 84.7 euros per ton of input WEEE.

3.3.2.2 Cooling and freezing appliances

Regarding cooling and freezing appliances, the Portuguese infrastructure includes three operators. Their individual economic performance was modelled based on the operations that each one performs when processing cooling and freezing appliances.

From the same example presented previously for cooling and freezing appliances, Figure 3.29 presents the economic performance of the operations that comprise one technology installed in a specific operator of the Portuguese infrastructure. The cost and revenue are presented considering the input of 1 ton of cooling and freezing appliances.

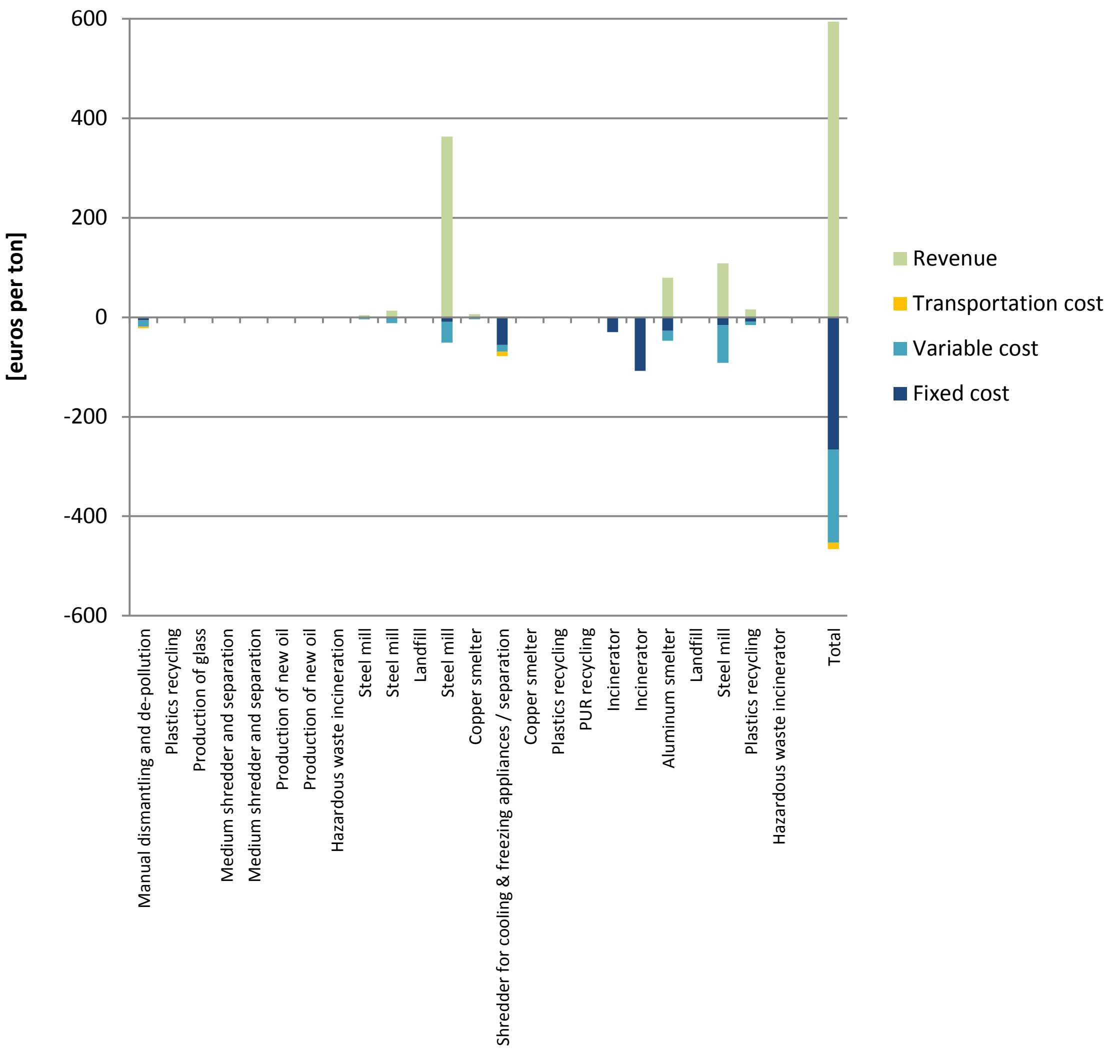


Figure 3.29 – Contribution per operation to the economic balance of the processing of cooling and freezing appliances

Figure 3.30 shows the total economic balance of the processing of cooling and freezing appliances for each of the operators in the Portuguese infrastructure, including the operations downstream of this. The operators are sorted from the highest to the lowest economic balance.

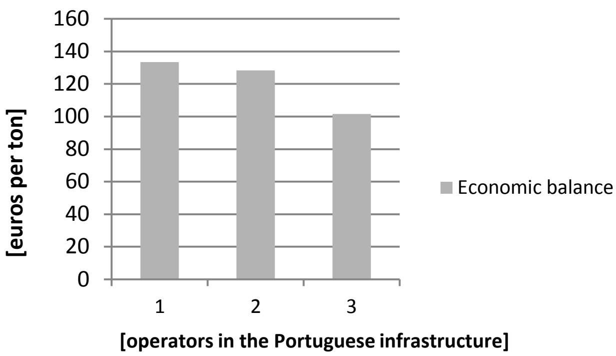


Figure 3.30 –Economic performance of cooling and freezing appliances achieved by the operators in the Portuguese infrastructure

The results indicate that the processing of cooling and freezing appliances has a positive economic balance for all operators that vary between 101.6 and 133.5 euros per ton of input WEEE.

3.3.2.3 Small domestic appliances

Considering the example presented previously for small domestic appliances, Figure 3.31 presents the economic performance of each of the operations that comprise the technology installed in one of the operators in the Portuguese infrastructure.

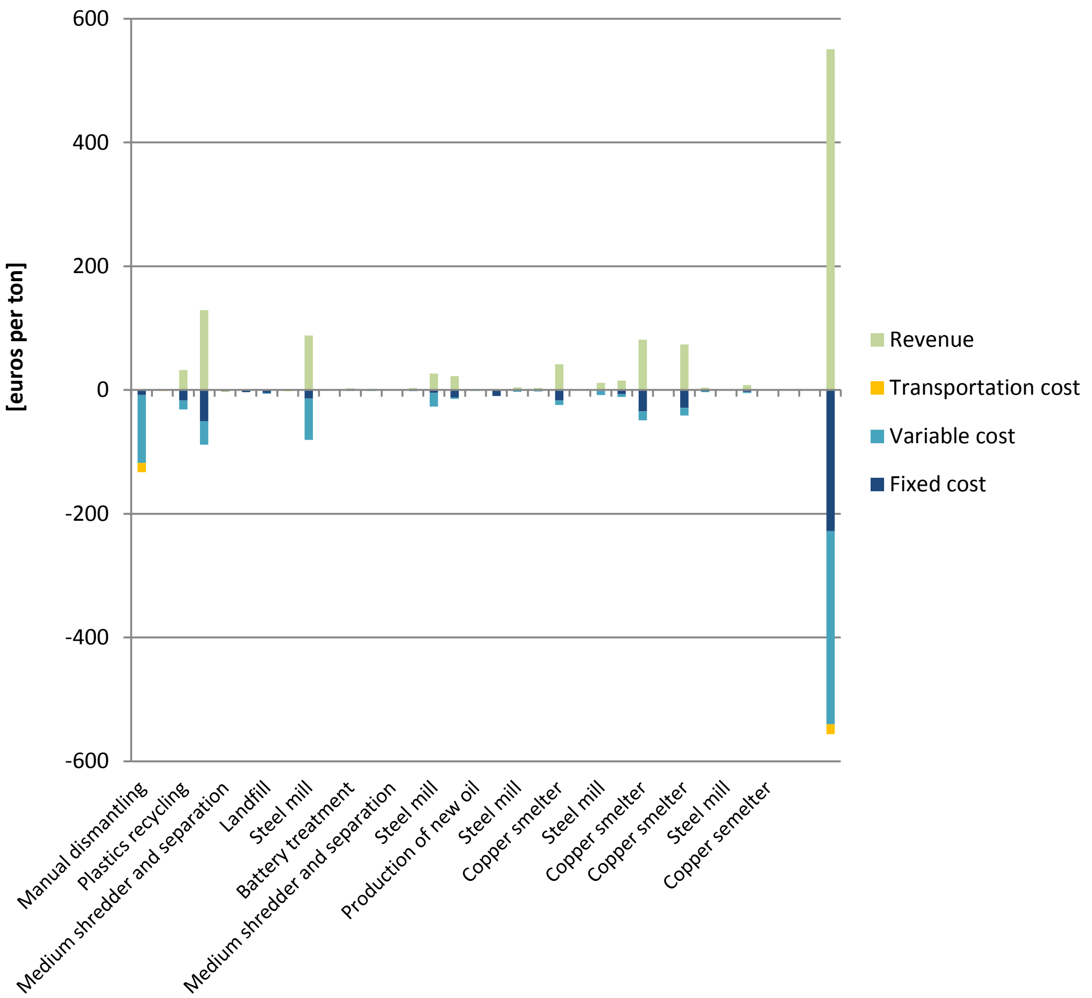


Figure 3.31 – Contribution per operation to the economic balance of the processing of small domestic appliances

Figure 3.32 shows the total economic balance of the processing of small domestic appliances for the operators in the Portuguese infrastructure, including the operations downstream of this. The operators are sorted from the highest to the lowest economic balance.

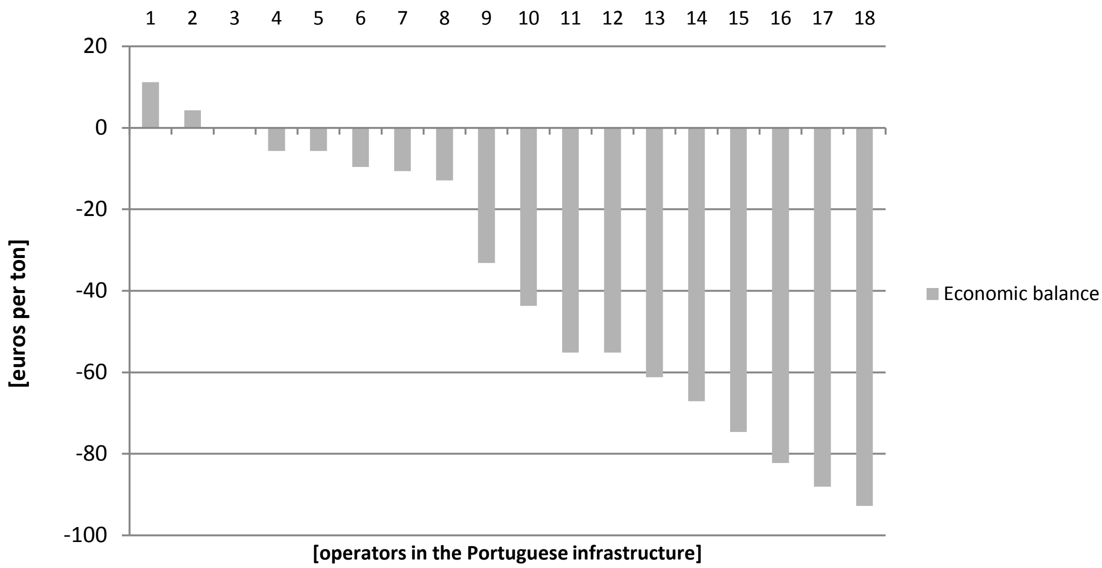


Figure 3.32 –Economic performance of processing small domestic appliances achieved by the operators in the Portuguese infrastructure

The total economic balance of processing small domestic appliances varies among the operators between 11.2 and -92.8 euros per ton of input WEEE.

3.3.2.4 Gas discharge lamps

Figure 3.33 presents the economic balance of one technology installed in an operator in the Portuguese infrastructure, divided in the individual contributions of the operations that constitute it. The data is presented in euros per ton of gas discharge lamps processed. The outcome of the total economic balance for gas discharge lamps processed is a negative value of -297.1 euros per ton of input WEEE.

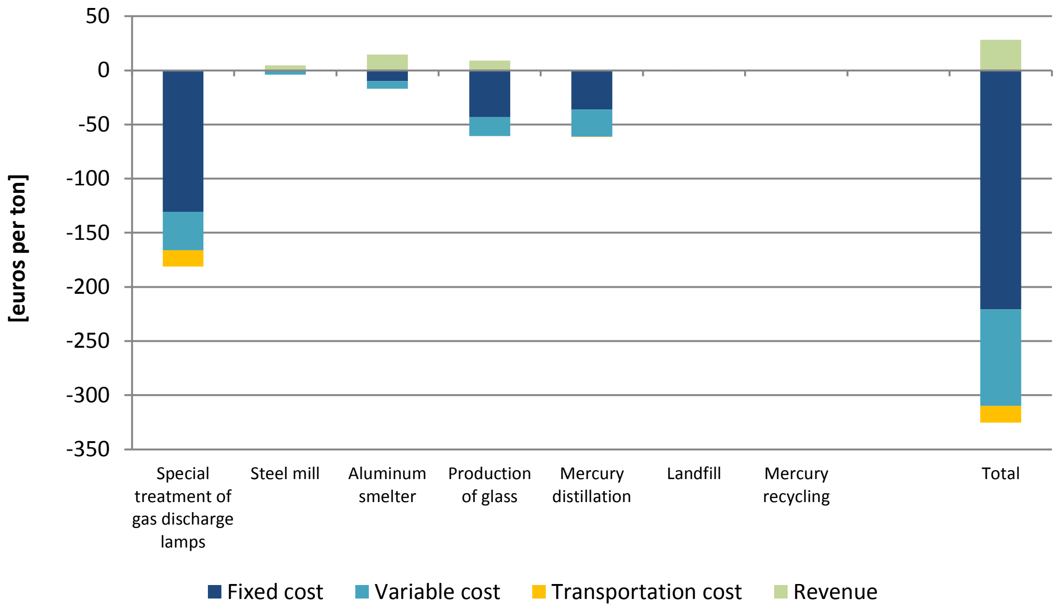


Figure 3.33 – Contribution per operation to the economic balance of the processing of gas discharge lamps

Figure 3.34 shows the total economic balance of the processing of gas discharge lamps for the operators in the Portuguese infrastructure, including the operations downstream of this. The operators are sorted from the highest to the lowest economic balance.

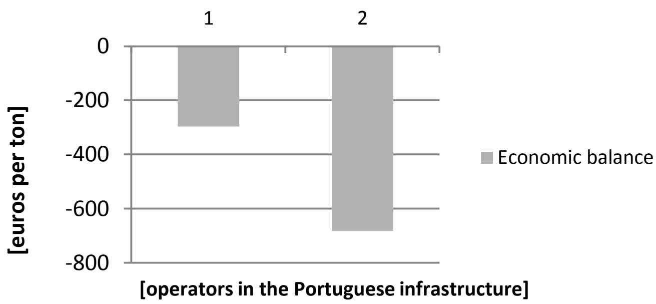


Figure 3.34 –Economic performance of processing gas discharge lamps achieved by the operators in the Portuguese infrastructure

The economic balance is negative in both operators.

3.3.2.5 CRT televisions and monitors

Considering the example presented previously for CRT televisions and monitors, Figure 3.35 shows the economic balance for one operator in the Portuguese infrastructure and the respective installed technology, with the contributions by the individual operations, in euros per ton of input to the first operation. The economic balance for CRT televisions and monitors processed in this case is a negative value of -11.4 euros per ton of input WEEE.

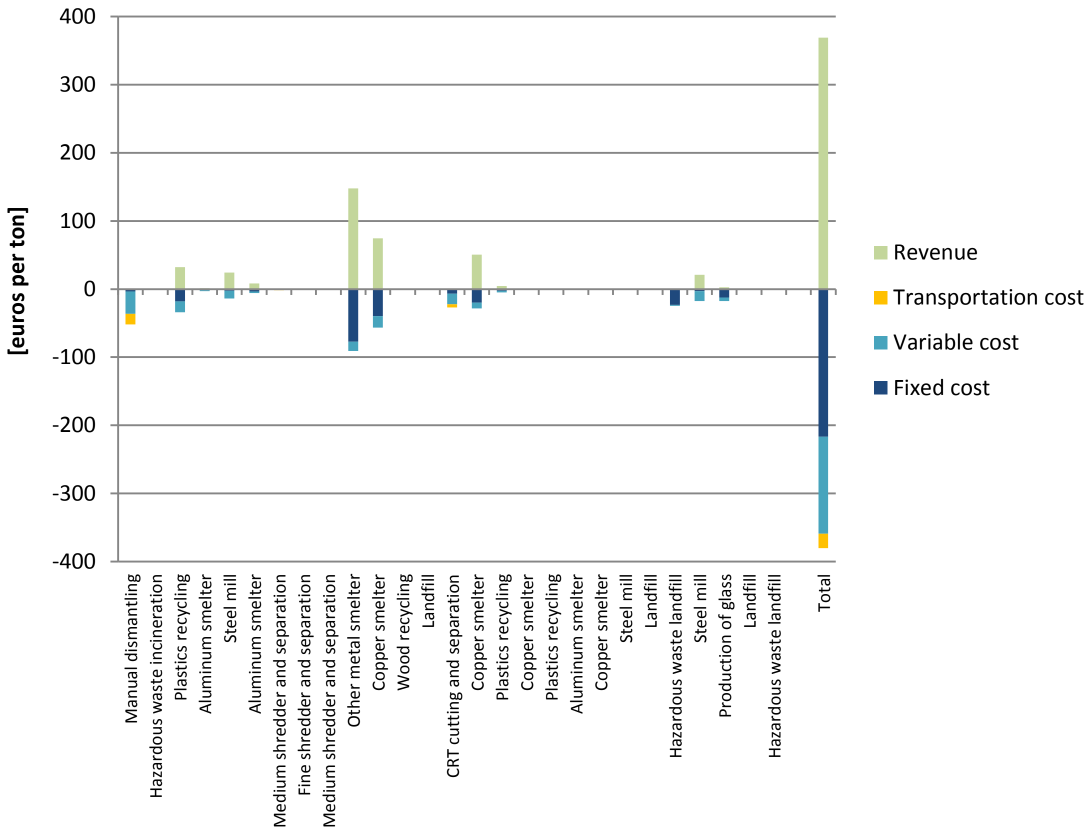


Figure 3.35 – Contribution per operation to the economic balance of the processing of CRT televisions and monitors

Figure 3.36 shows the total economic balance of the processing of CRT televisions and monitors for the operators in the Portuguese infrastructure, including the operations downstream of this. The operators are sorted from the highest to the lowest economic balance.

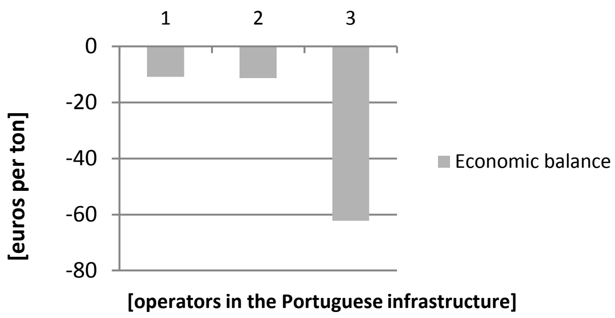


Figure 3.36 –Economic performance of processing CRT televisions and monitors achieved by the operators in the Portuguese infrastructure

The results indicate negative values for the three operators that vary between -10.9 and -62.2 euros per ton of input WEEE.

3.3.3 Environmental aspects

The models were developed to account the environmental impacts of end-of-life processing of the WEEE considering the operations, processing techniques and technologies installed in the Portuguese infrastructure, and downstream of this. Using LCA and the ReCiPe method previously described, the environmental impacts of each operation were calculated and the respective data was then used to develop the environmental aspects in the global model. The results are presented in normalization points, which are equivalent to the total environmental impacts of an average European citizen per year (PRé Consultants, 2008).

3.3.3.1 Large household appliances

Considering the example previously described for processing large household appliances, Figure 3.37 presents the results for one technology installed by a specific operator in the Portuguese infrastructure and the environmental contributions of each of the comprising operations.

For the given example, the environmental performance represents a value of -0.73 normalization points per ton of input WEEE (environmental impacts with a negative value represent an environmental gain).

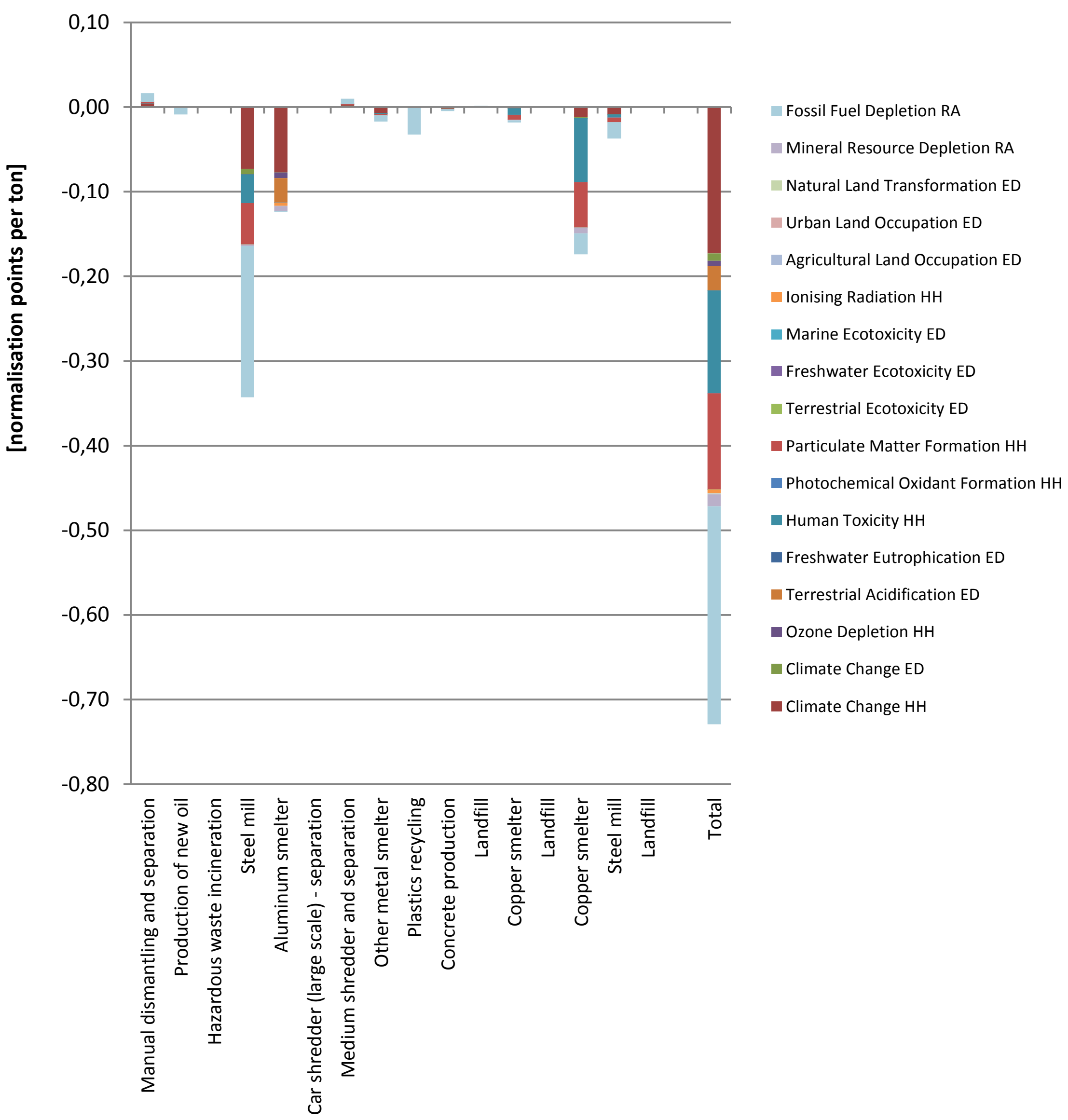


Figure 3.37 – Contribution per operation to the environmental balance of the processing of large household appliances

Figure 3.38 shows the total environmental performance of the treatment and recovery of large household appliances for each of the operators in the Portuguese infrastructure including all the downstream operations. The operators are sorted in the chart by decreasing environmental performance.

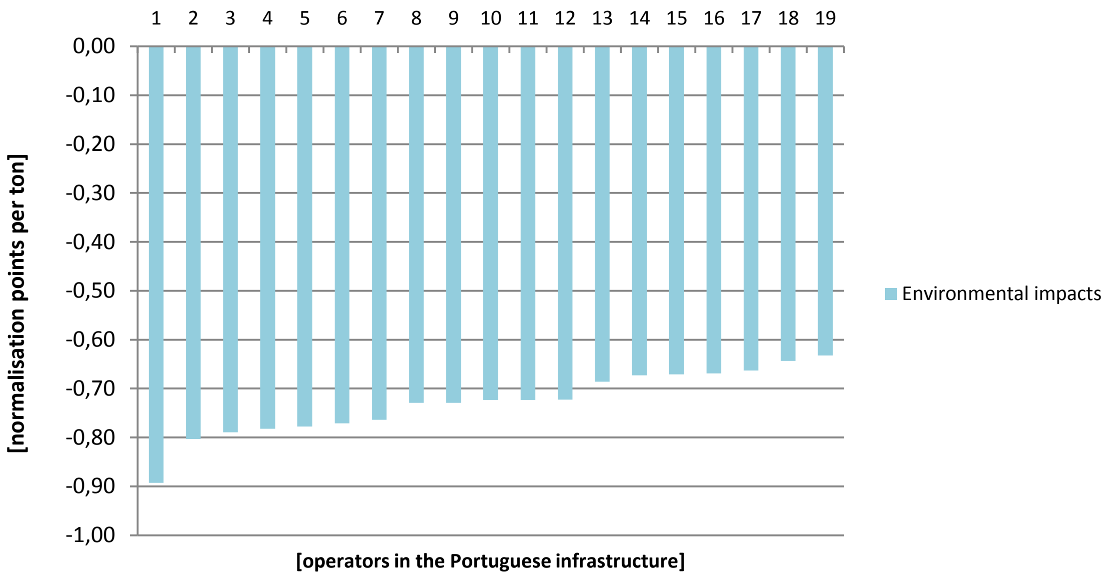


Figure 3.38 –Environmental performance of large household appliances achieved by the operators in the Portuguese infrastructure

The results indicate that the treatment and recovery of large household appliances represents an environmental gain in all operators that can range from -0.89 to -0.63 normalization points per ton of input WEEE.

3.3.3.2 Cooling and freezing appliances

Considering the example previously described for processing cooling and freezing appliances, Figure 3.39 presents the results for one operator of the Portuguese infrastructure and the installed technology, with environmental contributions of each of the operations that are part of it. The overall performance of WEEE treatment and recovery in this example corresponds to an environmental gain of -0.89 normalization points per ton of input WEEE.

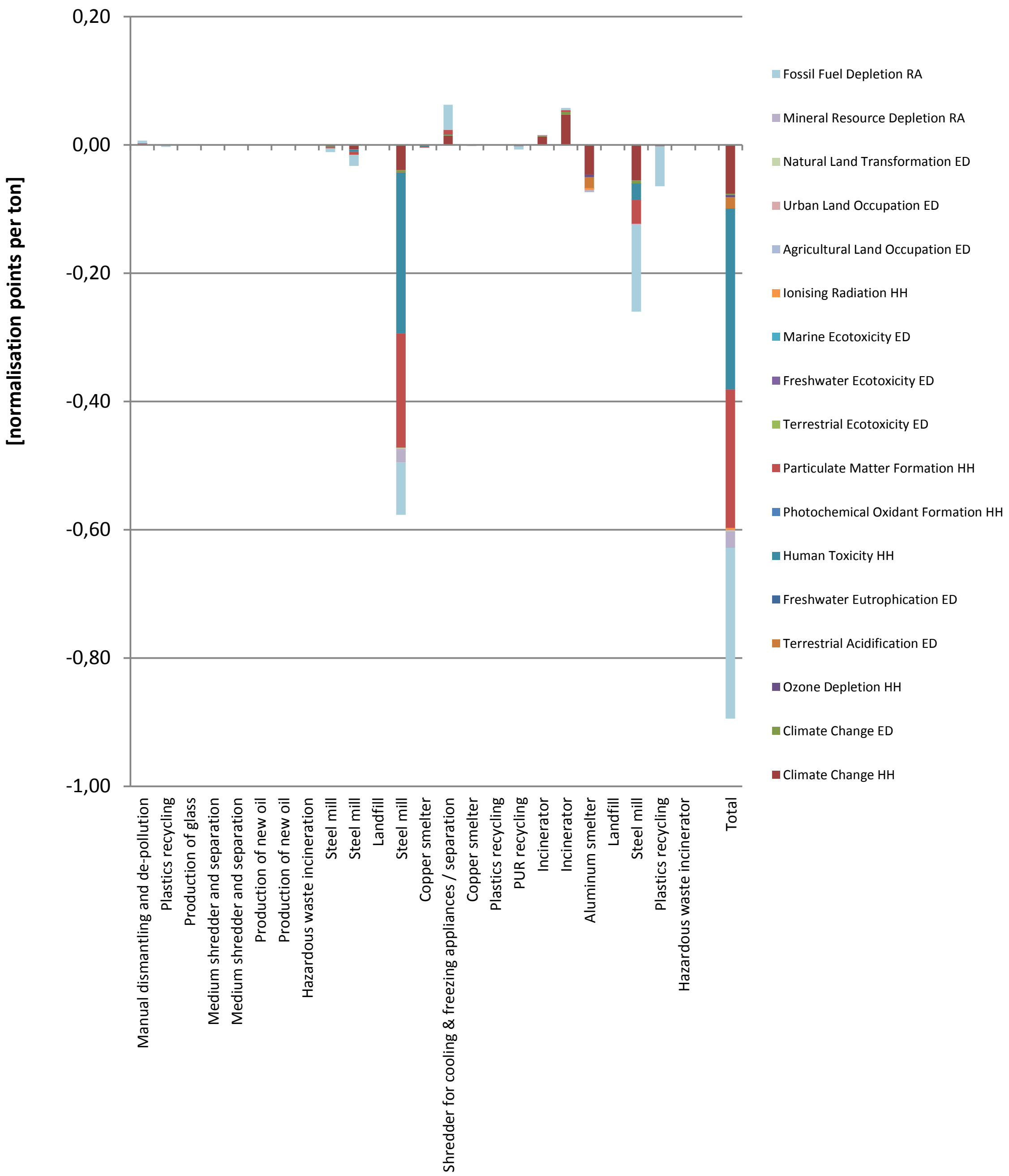


Figure 3.39 – Contribution per operation to the environmental balance of the processing of cooling and freezing appliances

Considering the Portuguese infrastructure and the operations downstream of this, Figure 3.40 shows the environmental performance of the three operators that provide the treatment and recovery of cooling and freezing appliances in Portugal. The operators are sorted from the highest to the lowest environmental performance.

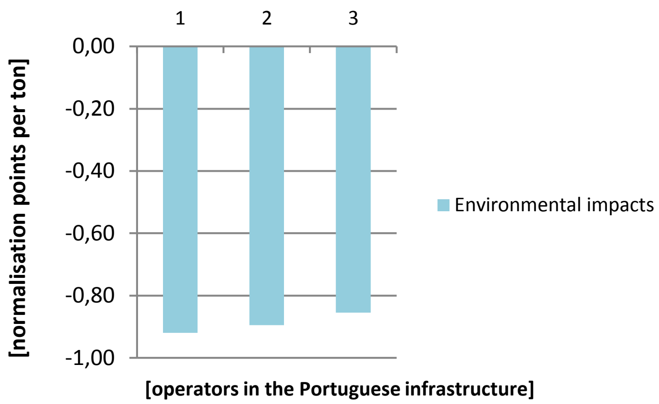


Figure 3.40 –Environmental performance of cooling and freezing appliances achieved by the operators in the Portuguese infrastructure

The results show that the treatment and recovery of cooling and freezing appliances represents an environmental gain regardless of the operators in the Portuguese infrastructure that perform it, and that it can range from -0.92 to -0.86 normalization points per ton of input WEEE.

3.3.3.3 Small domestic appliances

Considering the example previously described for processing small domestic appliances, Figure 3.41 presents the environmental contributions of each of the operations that constitute the technology installed by the given operator of the Portuguese infrastructure. With the exception of one operation with significant environmental load, most operations present significant environmental gains. Overall, the performance of WEEE treatment and recovery in this example corresponds to an environmental gain of -0.69 normalization points per ton of input WEEE (environmental impacts with a negative value represent an environmental gain).

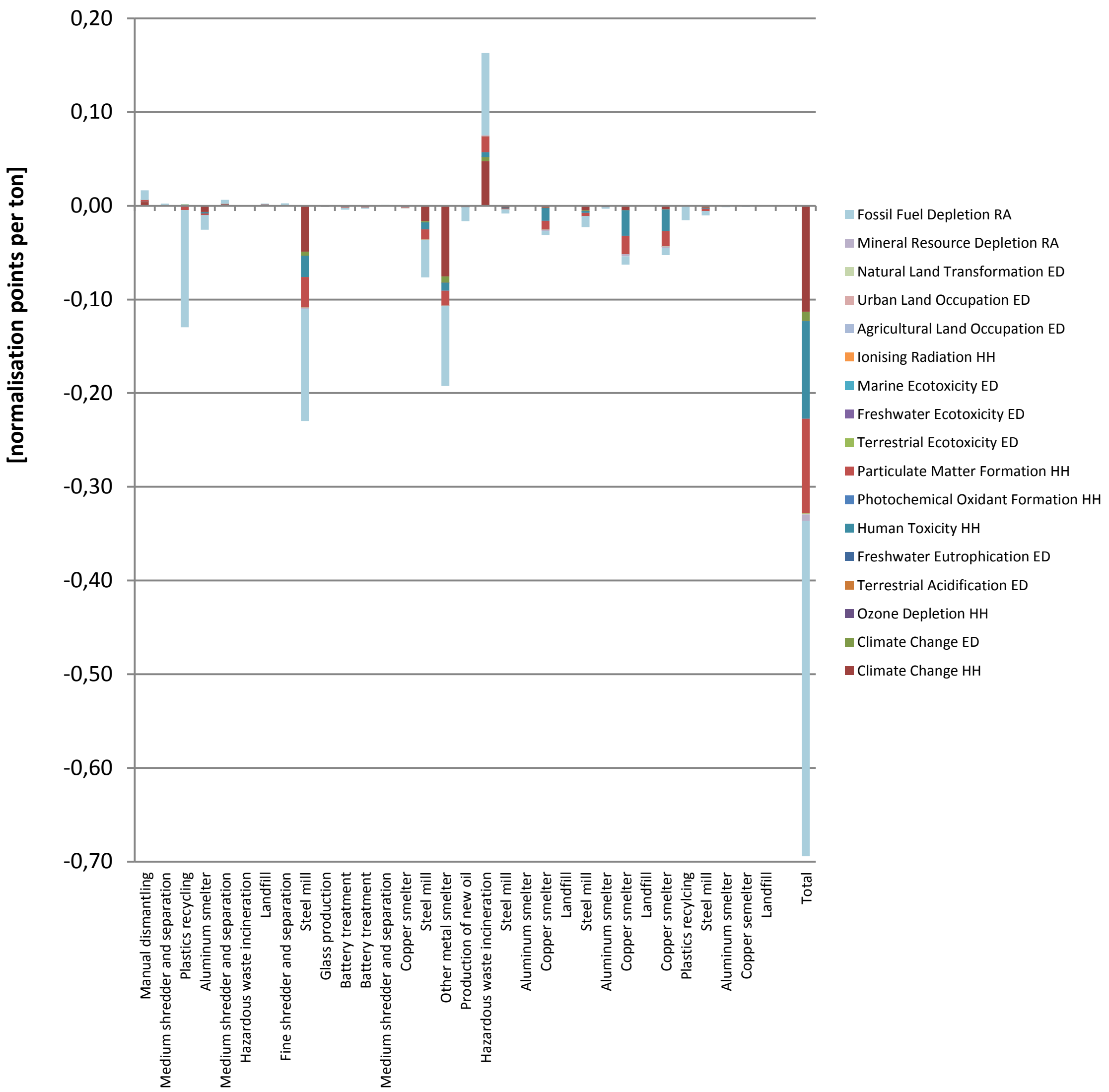


Figure 3.41 – Contribution per operation to the environmental balance of the processing of small domestic appliances

Figure 3.42 shows the environmental performance of the treatment and recovery of small domestic appliances for each of the operators in the Portuguese infrastructure, including all the downstream operations. The operators are sorted by decreasing environmental performance.

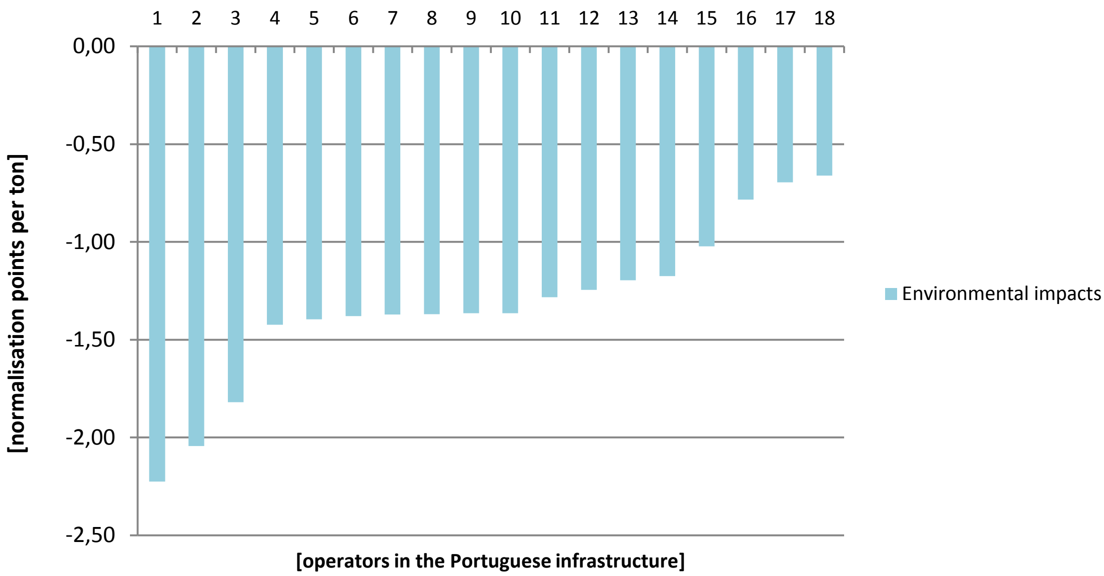


Figure 3.42 –Environmental performance of processing small domestic appliances achieved by the operators in the Portuguese infrastructure

The results show that the treatment and recovery of small domestic appliances represents an environmental gain in all operators, which can vary between -2.23 and -0.66 normalization points per input WEEE.

3.3.3.4 Gas discharge lamps

Figure 3.43 presents the results for a specific operator in the Portuguese infrastructure and the installed technology, showing the environmental contributions of each of the respective operations. The first operation has a significant environmental load and there are two operations with significant environmental gains. The remaining operations have little impact.

The total environmental performance of WEEE treatment and recovery in this example corresponds to an environmental gain of -0.30 normalization points per ton of input WEEE.

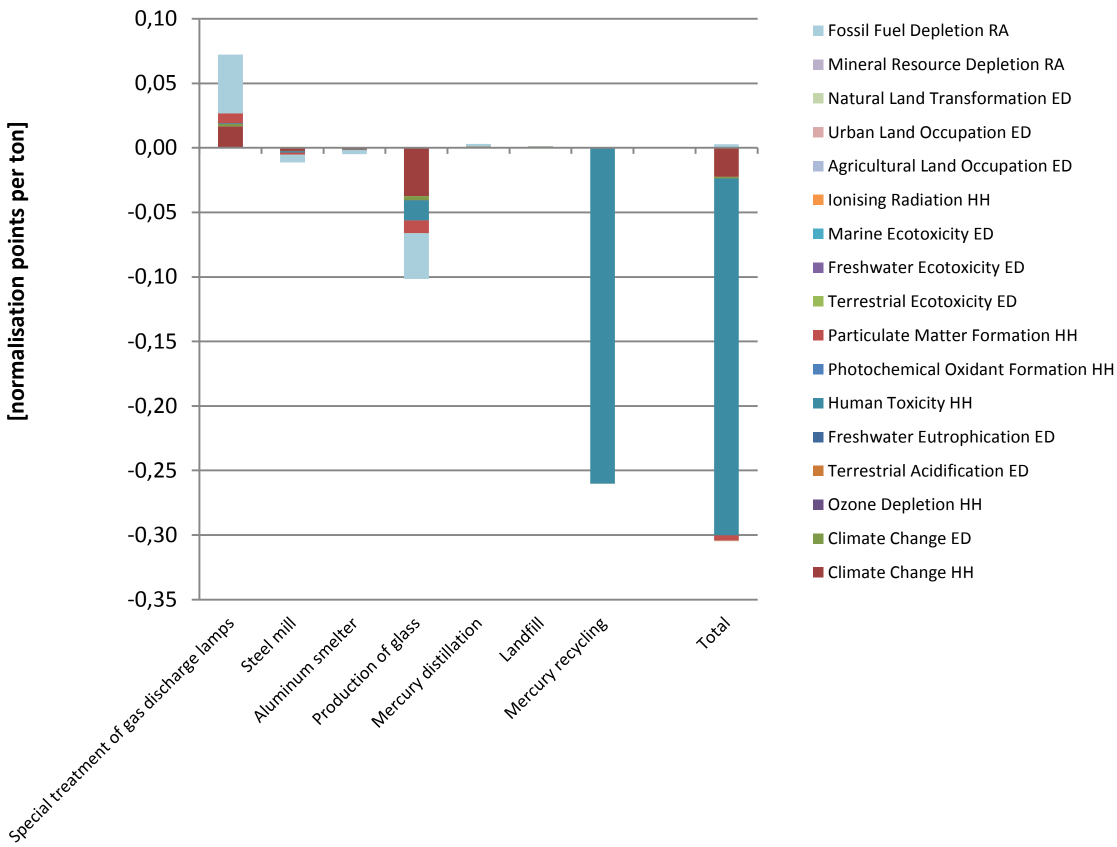


Figure 3.43 – Contribution per operation to the environmental balance of the processing of gas discharge lamps

Figure 3.44 shows the environmental performance of the treatment and recovery of gas discharge lamps for each of the operators in the Portuguese infrastructure, including the respective downstream operations.

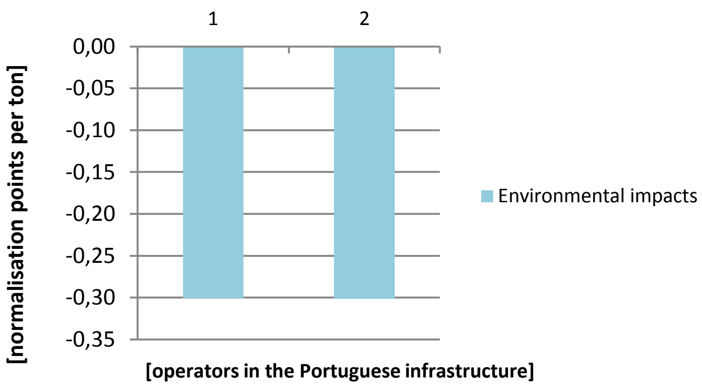


Figure 3.44 –Individual environmental performance of processing gas discharge lamps per technology in the Portuguese infrastructure

The environmental performances of both operators are very similar and account for an environmental gain of approximately -0.30 normalization points per ton of input WEEE.

3.3.3.5 CRT televisions and monitors

Figure 3.45 presents the results for the technology installed by one operator of the Portuguese infrastructure, namely the environmental contributions of each of the comprising operations. The results show that the environmental gains are largely superior to the environmental loads and, consequently, the total performance of WEEE treatment and recovery in this example corresponds to an environmental gain of -0.65 normalization points per ton of input WEEE.

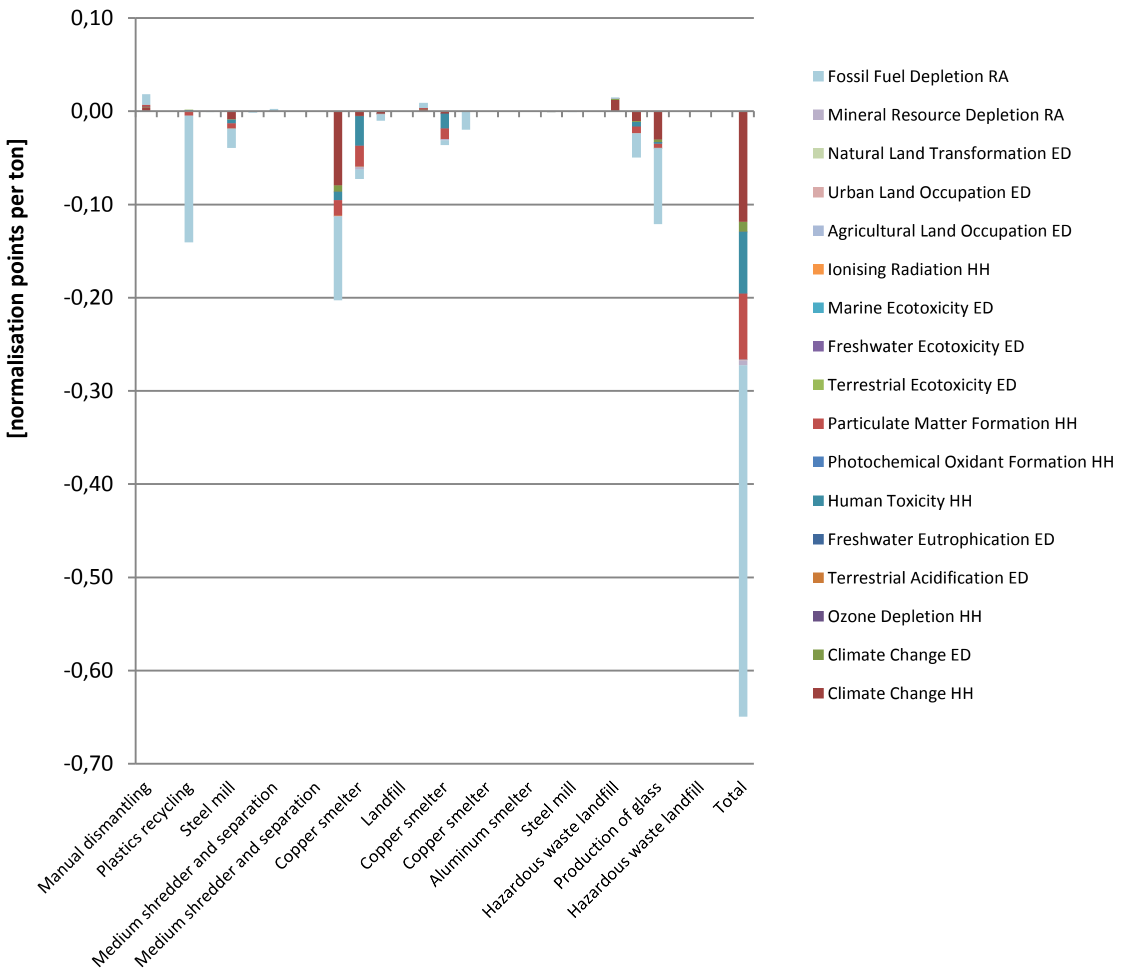


Figure 3.45 – Contribution per operation to the environmental balance of the processing of CRT televisions and monitors

Figure 3.46 shows the environmental performance of the treatment and recovery of CRT televisions and monitors performed by each of the operators in the Portuguese infrastructure, including the operations downstream of this. The operators are sorted in the chart according with a decreasing environmental performance.

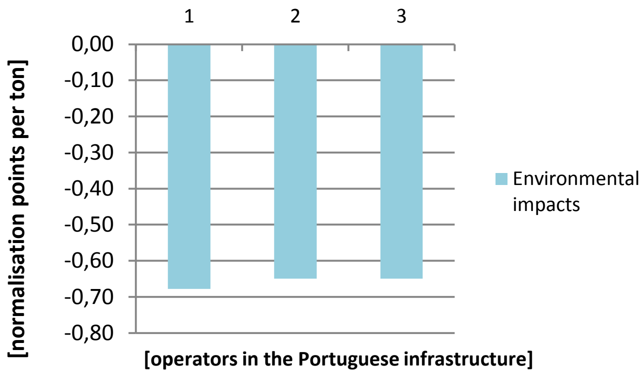


Figure 3.46 –Environmental performance of processing CRT televisions and monitors achieved by the operators in the Portuguese infrastructure

The results show that for all three different operators the treatment and recovery of CRT televisions and monitors represents an environmental gain, which can vary between -0.68 and -0.65 normalization points per ton of input WEEE.

4 Case study: Improving the WEEE treatment and recovery in Portugal

4.1 Assessment of the current performance of WEEE treatment and recovery

Every year a significant amount of WEEE is generated in Portugal and it has to be managed in the appropriate way to protect the human health and the environment. As it has been referred previously, within the legal framework of the WEEE Directive, the PRO's are legally responsible for the collection, treatment and recovery of WEEE. In particular, the PRO's have to ensure a minimum amount of collection of WEEE, which is presently defined by the legal target of 4 kilograms per inhabitant per year, adjusted by the market share of the producers associated with the PRO (in percentage by weight of the products placed on the market). There are currently no collection targets specifically for each of the distinct WEEE treatment categories, although there may be in the future, as the WEEE Recast incorporates such possibility.

For the WEEE amounts that have been collected, the PRO's also have to provide for the specific treatment of WEEE, including the removal of hazardous substances and components, and achieve the legal targets establishing the minimum percentage of reuse/recycling and recovery of WEEE. Currently, these targets are specified for the different types of products included in the distinct categories of WEEE, but in the future they may be defined specifically for the WEEE categories, based on the contents of the WEEE Recast.

The facts together, mean that although the WEEE is independently processed in the five distinct categories, the PRO's performance is measured in legal terms by the total score achieved in the management of the WEEE of all categories. In the future this may be different, based on the WEEE Recast.

In order to take full legal responsibility on the management of WEEE and achieve the designated legal targets, the PRO's develop an infrastructure that takes care of the operations. The Portuguese infrastructure, along with a series of downstream operators, serves the PRO's in Portugal (AMB3E and ERP Portugal) and process the WEEE that these organizations collect.

Based on the models previously described, the specific performance of the end-of-life processing of all five categories of WEEE was assessed for the operators in the Portuguese infrastructure and downstream of this, considering the technical, economic and environmental aspects. Following this, the absolute performance is calculated, considering the amounts of WEEE per category that each of the operators in the Portuguese infrastructure will process.

A method is proposed and used in the research to determine the absolute performance of the WEEE treatment and recovery achieved in the Portuguese infrastructure. The method includes four distinct indicators: the reuse and recycling (in percentage), the recovery (in percentage), the economic balance (in euros) and the environmental balance (in normalization points).

In each indicator, the absolute value for the Portuguese infrastructure is calculated based on the specific value, per ton of WEEE, achieved by each individual operator and the respective

amounts per category of WEEE to be processed also by each individual operator. The indicators present the aggregated value, for the WEEE treatment categories all together.

The absolute performance of the WEEE management in the Portuguese infrastructure is mathematically formulated in Equation 4.1 to Equation 4.4.

Notice that the technical performance – recycling and recovery – of the Portuguese infrastructure was assessed against the legal targets, for which reason the definitions of recycling and of recovery used are based on those from the waste framework directive (European Commission, 2008).

Equation 4.1 – WEEE reuse and recycling in the Portuguese infrastructure

$$Reuse \; \& \; Recycling \; total \; (in \; percentage) = \sum_{c} \sum_{i} (Aic \; \times RRic \;) \; / \; Ac$$

where c = 1, …, 5 categories of WEEE, i = 1, ..., processing operators for each category of WEEE.

Ac is the total amount of WEEE (in ton) per category c, Aic is the amount of WEEE (in ton) of category c that is processed by each operator i with the reuse/recycling performance equal to RRic (in percentage).

Equation 4.2 – WEEE recovery in the Portuguese infrastructure

$$Recovery \; total \; (in \; percentage) = \sum_{c} \sum_{i} (Aic \; \times Ric \;) \; / \; Ac$$

where c = 1, …, 5 categories of WEEE, i = 1, ..., processing operators for each category of WEEE.

Ac is the total amount of WEEE (in ton) per category c, Aic is the amount of WEEE (in ton) of category c that is processed by each operator i with the recovery performance equal to Ric (in percentage).

Equation 4.3 – Economic balance in the Portuguese infrastructure

$$Economic \; balance \; total \; (in \; euros) = \sum_{c} \sum_{i} (Aic \; \times Cic \;)$$

where c = 1, …, 5 categories of WEEE, i = 1, ..., processing operators for each category of WEEE.

Aic is the amount of WEEE (in ton) of category c that is processed by each operator i with the economic performance equal to Cic (in euros per ton).

Equation 4.4 – Environmental balance in the Portuguese infrastructure

$$Environmental\ balance\ total\ (in\ normalization\ points) = \sum_{c} \sum_{i} (Aic\ \times Lic\ )$$

where c = 1, …, 5 categories of WEEE, i = 1, ..., processing operators for each category of WEEE.

Aic is the amount of WEEE (in ton) of category c that is processed by each operator i with the environmental performance equal to Lic (in normalization points per ton).

Two determining aspects were required to calculate the current performance of the treatment and recovery of WEEE in the Portuguese infrastructure: the amounts of WEEE to be collected and processed in 2012 and the respective allocation per operator.

Regarding the amount of WEEE collection it was calculated based on the sales volumes of EEE in the Portuguese market over the past two decades (ANREEE, 2007 to 2012) and considering the respective average life time of the products sold (see detailed description in Annex III).

Table 4.1 presents the calculated amounts of WEEE to be collected in 2012 in Portugal, by AMB3E and ERP Portugal, per treatment category. The collection rate is approximately 4.6 kilograms per inhabitant per year, considering the resident population of Portugal (INE, 2012), which is above the current collection legal target (4 kilograms per inhabitant per year) (European Commission, 2003b).

The collected amounts in 2012 were expected to be lower than the previous year. The economic crisis in Portugal resulted in the reduction of overall waste production and in increase competition by operators from the informal sector.

Table 4.1 – Amount of WEEE to be collected in the Portuguese infrastructure in 2012

Treatment category	WEEE collected and processed (kg)
Large household appliances (A)	18735651
Cooling and freezing appliances (B)	9579306
Small domestic appliances (C)	13509135
Gas discharge lamps (D)	591357
CRT televisions and monitors (E)	6589592
Total	**49005041**

Notes: Calculated based on the sales of EEE in Portugal (ANREEE, 2007 to 2012), considering the average life time of equipment (NIES, 2011) and the historic collection data in Portugal per treatment category (AMB3E, 2006 to 2012 and ERP Portugal 2009 and 2010).

Regarding the allocation of the amounts of WEEE to be processed in 2012 by the operators in the Portuguese infrastructure, this was calculated using historical data from AMB3E (AMB3E, 2006, 2007, 2008, 2009, 2010 and 2011) and limited by the maximum throughput per operator obtained from the WEEE processing tests.

Figure 4.1 presents the calculated allocation of the amounts of WEEE of each category per operator in the Portuguese infrastructure. This was used to determine the current total performance of the WEEE treatment and recovery in the infrastructure.

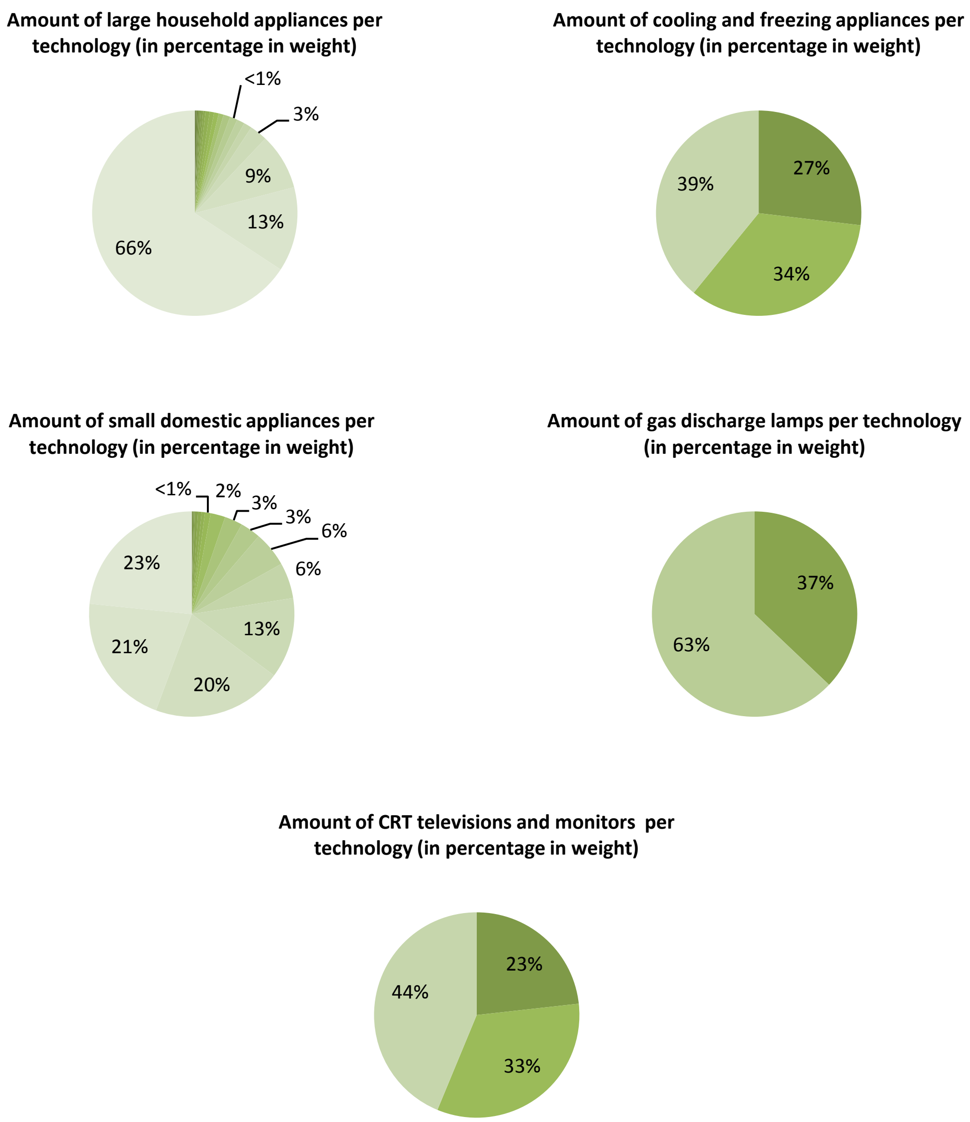


Figure 4.1 – Allocation of amounts of WEEE per operator in the Portuguese infrastructure in 2012

In the following sections the current total performance of the treatment and recovery of WEEE in the Portuguese infrastructure is presented, respectively considering the technical, economic and environmental aspects.

4.1.1 Technical performance

The WEEE collected by AMB3E and ERP Portugal is treated and recovered to ensure the achievement of the reuse/recycling and recovery rates.

Based on the individual technical performances assessed and presented in chapter 3 for each of the operators in the Portuguese infrastructure including the downstream operations, and the allocation of the amounts of WEEE to be processed by each one in 2012, the total performance regarding the reuse/recycling and recovery of WEEE was calculated.

Table 4.2 shows the resulting amounts of WEEE reused and recycled per category and the respective percentages in respect to the WEEE processed. It is possible to verify that the reuse/recycling performance is comfortably above the legal targets for treatment categories A, C and D, while for categories B and E it is very close to the current legal target (in the case of cooling and freezing appliances is just under it).

Table 4.2 – WEEE reuse and recycling in the Portuguese infrastructure in 2012

Treatment categories	Reuse/recycling (t)	Reuse/recycling (%/t of input WEEE)	Legal targets (%)
Large household appliances (A)	16068.3	85.8	75.0
Cooling and freezing appliances (B)	7152.1	74.7	75.0
Small domestic appliances (C)	10790.7	79.9	56.4
Gas discharge lamps (D)	545.6	92.3	80.0
CRT televisions and monitors (E)	4299.3	65.2	65.0
Total	**38856.1**	**79.3**	**-**

Notes: Calculated based on individual reuse/recycling performance (%) of each operator in the Portuguese infrastructure and the respective amount of WEEE allocated for processing in 2012 (ton).

Table 4.3 presents the amounts of WEEE recovered per category and the respective percentages in respect to the WEEE processed. Because energy recovery is not a significant final destination of WEEE in the Portuguese infrastructure, the WEEE recovery is similar to the result of reuse and recycling.

However, the legal targets on recovery are higher and the performance for categories B and E is well below the minimum levels required. In categories A, C and D the current legal targets are fulfilled.

Table 4.3 – WEEE recovery in the Portuguese infrastructure in 2012

Treatment categories	Recovery (t)	Recovery (%/t of input WEEE)	Legal targets (%)
Large household appliances (A)	16068.3	85.8	80.0
Cooling and freezing appliances (B)	7282.3	76.0	80.0
Small domestic appliances (C)	10852.7	80.3	71.2
Gas discharge lamps (D)	545.6	92.3	-
CRT televisions and monitors (E)	4299.3	65.2	75.0
Total	**39048.3**	**79.7**	**-**

Notes: Calculated based on individual recovery performance (%) of each operator in the Portuguese infrastructure and the respective amount of WEEE allocated for processing in 2012 (ton).

An additional aspect to have in consideration is the upcoming legal targets defined in the WEEE Recast to be applicable by 2016: on average there is a 5 percentage points increase on the current target values. This adds more pressure and makes it even more evident that is necessary to improve the technical performance of the entire end-of-life processing chain for WEEE, including the part of it that constitutes the Portuguese infrastructure.

4.1.2 Economic performance

In a similar method to the one described previously, the economic performance of WEEE processing in the Portuguese infrastructure in 2012 was calculated. The individual economic performance of the operators assessed in chapter 3 and the respective amounts of WEEE allocated to be processed in 2012 were considered to calculate the total economic performance.

Table 4.4 presents the economic balance per category for the WEEE processed in the Portuguese infrastructure, including the downstream operations. The results indicate that the processing of WEEE of categories A and B generates a positive economic balance, while for treatment categories C, D and E a negative value is achieved. Overall, the treatment and recovery of WEEE presents a positive economic value in all categories.

Table 4.4 – Economic balance of WEEE treatment and recovery in the Portuguese infrastructure in 2012

Treatment categories	Economic balance (€)	Economic balance (€/t of input WEEE)
Large household appliances (A)	1084339.7	57.9
Cooling and freezing appliances (B)	1177169.0	122.9
Small domestic appliances (C)	-140013.4	-10.4
Gas discharge lamps (D)	-319008.3	-539.5
CRT televisions and monitors (E)	-151640.7	-23.0
Total	**1650846.4**	**33.7**

Notes: Calculated based on individual economic performance (euros per ton) of each operator in the Portuguese infrastructure and the respective amount of WEEE allocated for processing in 2012 (ton).

According with the WEEE Directive the producers of EEE are financially responsible for the management of WEEE. The PRO's, as representing organizations of the producers of EEE are licensed by government authorities and have to provide the financial assistance for the operations of WEEE management, in particular the end-of-life processing to ensure the fulfilment of the selective treatment requirements and the reuse/recycling and recovery targets.

Considering the current EPR based WEEE management systems, the different types of products should respond for their own economic balance; this means that for WEEE of the categories that have a negative economic balance the PRO's have to provide financial assistance to ensure the treatment and recovery. Table 4.5 shows the calculated minimum financial assistance required to ensure the treatment and recovery of WEEE in the Portuguese infrastructure in 2012.

Table 4.5 – Financial assistance required for WEEE treatment and recovery in the Portuguese infrastructure in 2012

Treatment categories	Required financial assistance (€)	Required financial assistance (€/t of input WEEE)
Large household appliances (A)	0.0	0.0
Cooling and freezing appliances (B)	0.0	0.0
Small domestic appliances (C)	-140013.4	-10.4
Gas discharge lamps (D)	-319008.3	-539.5
CRT televisions and monitors (E)	-151640.7	-23.0
Total	**-610662.4**	**-12.5**

Notes: It is assumed that PRO's don't need to provide financial assistance in the WEEE categories where the economic balance is positive, in which cases the market should function by itself.

In theory, PRO's in Portugal would need to provide financial assistance only for the processing of WEEE of categories C, D and E. For categories A and B no financial assistance would be necessary; additionally this presents an opportunity for PRO's to develop additional sources of revenue other than the respective associate producers (ecovalue), for example by entering the business of WEEE processing instead of just hiring the services.

It is important to highlight that the models developed were designed to cancel one of the main economic inefficiencies - speculation in trade between operators - and calculate the value closest to the intrinsic economic value of the end-of-life processing of the WEEE. In this context, the lean economic performance was presented and this may differ from the economic balance experienced in practice by PRO's, which may include various economic inefficiencies resulting from the trade between the stakeholders in the end-of-life processing chain for WEEE.

4.1.3 Environmental performance

The environmental performance of WEEE treatment and recovery in the Portuguese infrastructure, including all the downstream operations, was calculated based on the individual performance of the operators assessed in chapter 3, and the respective amounts of WEEE allocated for processing by each one. Table 4.6 presents the resulting total environmental impacts of WEEE treatment and recovery in 2012 per category.

Table 4.6 – Environmental performance of WEEE treatment and recovery in the Portuguese infrastructure in 2012

Treatment categories	Environmental impacts (normalization points)	Environmental impacts (normalization points /t of input WEEE)
Large household appliances (A)	-13203.7	-0.70
Cooling and freezing appliances (B)	-8503.6	-0.89
Small domestic appliances (C)	-16949.2	-1.25
Gas discharge lamps (D)	-178.1	-0.30
CRT televisions and monitors (E)	-4342.5	-0.66
Total	**-43177.1**	**-0.88**

Notes: Calculated based on individual environmental performance (normalization points per ton) of each operator in the Portuguese infrastructure and the respective amount of WEEE allocated for processing in 2012 (ton).

In all treatment categories the results represent environmental gains. This was expected as the calculation includes the treatment and the recovery of the materials and energy content of WEEE. The overall WEEE treatment and recovery in the Portuguese infrastructure represented on average -0.88 normalization points per ton of input WEEE; this is equivalent to saving approximately 88% of the total environmental impacts of an average European citizen per year.

4.2 Improving the treatment and recovery of WEEE

The results indicate that it is necessary to improve the current performance of end-of-life processing of WEEE and that the PRO's face serious challenges to ensure the achievement of the upcoming more ambitious reuse/recycling and recovery targets, while minimizing the cost and increasing the environmental gains of the WEEE treatment and recovery.

One important objective of the research was to demonstrate the use of the global model to improve the treatment and recovery of WEEE. Following this objective, a more efficient and effective use of the end-of-life processing technologies was determined by recalculating the allocation of the amounts of WEEE collected in Portugal to the operators in the infrastructure in order to achieve specific designated improvement targets.

In essence, a mathematical model was formulated consisting of following components:

- Decision variables: these variables represent unknown quantities, namely the amounts of WEEE to be processed per operator in the Portuguese infrastructure;
- Objective function: the objective is expressed as a mathematical expression in decision variables. In the present case, the objective was established for the equations describing the performance of reuse/recycling, recovery, economic balance and environmental balance. Based on a combination of the technical, economic and environmental aspects, 6 scenarios were established to improve the performance of the treatment and recovery of the WEEE in the Portuguese infrastructure;
- Constraints: the limitations or requirements expressed as inequalities of equations in decision variables. In the present case study, various constraints were also defined according with the different objectives.

4.2.1 Improvement scenarios

In total, 6 different improvement scenarios were established, including various objective functions and constraints. Figure 4.2 presents a diagram of the scenarios considering the technical, economic and environmental aspects.

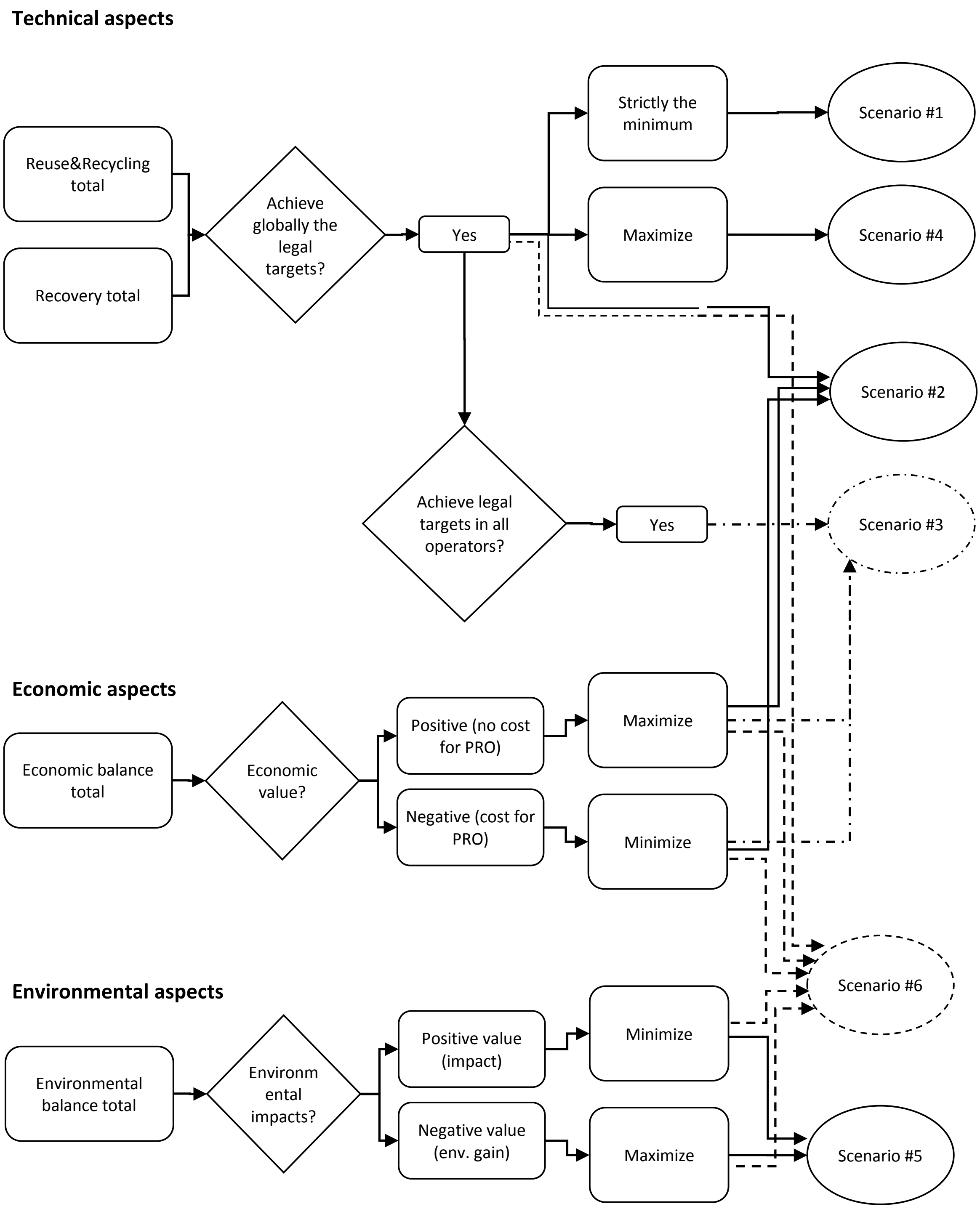


Figure 4.2 – Proposed improvement scenarios

The WEEE treatment and recovery performance in Portugal in 2012 was set as the baseline for the improvement (designated as #0 *Reference 2012*). Each of the improvement scenarios was

developed to incorporate the main directions under which the improvements of the treatment and recovery of WEEE can be promoted, using the PRO's and their take back systems. The 6 scenarios are described as follows:

- Scenario #1 (Minimum legal compliance): PRO's are required to fulfil legal requirements on selective treatment and also to achieve legal targets on the reuse/recycling and recovery of WEEE. This scenario was intended to determine the baseline performance of WEEE processing necessary to fulfil strictly the minimum legal requirements and targets on the treatment and recovery of WEEE;
- Scenario #2 (Low cost legal compliance): PRO's are legally responsible to finance the negative economic balance of WEEE treatment and recovery. They sign contracts with operators that individually have to fulfil legal requirements on selective treatment and globally have to ensure the achievement of legal targets on the reuse/recycling and recovery of WEEE. This scenario was intended to determine the minimum cost of compliance with legal requirements on treatment and targets on recovery;
- Scenario #3 (Low cost legal compliance & certification): similar to scenario #2 (Low cost legal compliance) with one difference: each operator of the infrastructure has to fulfil individually the legal targets on reuse/recycling and recovery of WEEE. The WEEE Directive establishes that Member States shall encourage operators which carry out treatment operations to introduce certified environmental management systems. In this context, it is assumed that the operators have to comply individually with legal requirements on treatment and recovery. The scenario intended to determine the minimum cost for the PRO's to sign contracts exclusively with certified WEEE processing operators;
- Scenario #4 (Maximum reuse/recycling and recovery): PRO's are required to fulfil legal requirements on selective treatment and also to achieve legal targets on reuse/recycling and recovery of WEEE. However, these requirements are expected to be more demanding in the future and it will be necessary to increase the rates of WEEE reuse/recycling and recovery achieved by the infrastructure. The present scenario was intended to determine the maximum reuse/recycling and recovery rates that the infrastructure is able to achieve;
- Scenario #5 (Maximum environmental gain): the motivation for WEEE treatment and recovery is primarily to protect the human health and prevent the impacts on the environment. PRO's are legally responsible to ensure the proper treatment and recovery of WEEE, but this is hardly a direct measure of the protection of human health and the environment, especially considering a total life cycle perspective. The present scenario was intended to improve the WEEE processing in order to maximize the environmental gains of WEEE treatment and recovery, regardless of the rates of reuse/recycling and recovery achieved;
- Scenario #6 (Sustainable): there are various definitions of sustainability, but they all express the notion of balance of three dimensions: economic, environmental and social. With the exception of the social dimension, the other dimensions have been considered

in the assessment of the performance of WEEE processing in the research work. As the previous scenarios all favoured one specific improvement direction, the present scenario intended to have a balance of the technical, economic and environmental aspects, by simultaneously complying with legal requirements, minimizing the cost and maximizing the environmental gains of WEEE treatment and recovery.

Table 4.7 summarizes each of the scenarios defined to improve the performance of WEEE treatment and recovery in Portugal, including the objectives and constraints.

Table 4.7 – Improvement scenarios

#	Scenario	Description	Objective function	Constraints
1	**Minimum legal compliance**	• Achieve strictly the minimum reuse/recycling rates of the WEEE collected. (Under these rules, it was possible to have part of the WEEE that had been collected being processed to remove the hazardous substances and components but not being further processed for recovery.)	Minimum (Reuse&Recycling total (in percentage) as in Equation 4.1) and Minimum (Recovery total (in percentage) as in Equation 4.2)	Reuse&Recycling total (in percentage) = 75% (for category A) 75% (for category B) 56% (for category C) 80% (for category D) 65% (for category E) and Recovery total (in percentage) = 80% (for category A) 80% (for category B) 71% (for category C) 80% (for category D) 75% (for category E)
2	**Low cost legal compliance**	• Achieve the reuse/recycling rates of the WEEE collected. • Maximize the economic balance of WEEE treatment and recovery. (The objective of these rules was to minimize the financial assistance that the PRO's would have to provide for WEEE processing operators to ensure the legal compliance with WEEE treatment and recovery requirements)	Maximum (Economic balance total (in euros) as in Equation 4.3)	Reuse&Recycling total (in percentage) ≥ 75% (for category A) 75% (for category B) 56% (for category C) 80% (for category D) 65% (for category E) and Recovery total (in percentage) ≥

#	Scenario	Description	Objective function	Constraints
				80% (for category A) 80% (for category B) 71% (for category C) 80% (for category D) 75% (for category E)
3	**Low cost legal compliance & certification**	• Achieve the reuse/recycling rates of the WEEE collected. • Achieve the reuse/recycling rates of the WEEE processed individually by technology. • Minimize the negative economic balance of WEEE treatment and recovery. (The objective of these rules was to minimize the financial assistance that the PRO's would have to provide for WEEE processing operators to ensure the individual legal compliance with WEEE treatment and recovery requirements.)	Maximum (Economic balance total (in euros) as in Equation 4.3)	Reuse&Recycling per technology (in percentage) ≥ 75% (for category A) 75% (for category B) 56% (for category C) 80% (for category D) 65% (for category E) and Recovery per technology (in percentage) ≥ 80% (for category A) 80% (for category B) 71% (for category C) 80% (for category D) 75% (for category E)
4	**Maximum reuse/recycling and recovery**	• Ensure the selective treatment of all WEEE collected. • Maximize the reuse/recycling rates of all the WEEE collected.	Maximum (Reuse&Recycling total (in percentage) as in Equation 4.1 and Maximum (Recovery total (in percentage) as in Equation 4.2)	-
5	**Maximum environmental gain**	• Maximize the environmental gains from WEEE treatment and recovery of all the collected WEEE.	Maximum (Environmental balance total (in normalization points) as in Equation 4.4)	-

#	Scenario	Description	Objective function	Constraints
6	**Sustainable**	• Achieve the reuse/recycling rates of the WEEE collected. • Minimize the negative economic balance of WEEE treatment and recovery. • Maximize the environmental gains from WEEE treatment and recovery of all the collected WEEE. (Under these rules, the legal compliance was mandatory, while the minimization of the cost and the maximization of the environmental gains were both weighted with the same importance.)	Maximum (Economic balance total (in euros) as in Equation 4.3) Maximum (Environmental balance total (in normalization point) as in Equation 4.4)	Reuse&Recycling total (in percentage) ≥ 75% (for category A) 75% (for category B) 56% (for category C) 80% (for category D) 65% (for category E) and Recovery total (in percentage) ≥ 80% (for category A) 80% (for category B) 71% (for category C) 80% (for category D) 75% (for category E)

Considering the specificities of the Portuguese infrastructure for end-of-life processing of WEEE, in order to obtain results closest to reality as possible, the following rules were set and applied to all scenarios:

- The amount of WEEE allocated to each of the operators was limited to the respective annual processing capacity per treatment category;
- Only the capacity of the Portuguese infrastructure was used, excluding exports of complete WEEE for processing (notice: exports of output fractions obtained from processing of WEEE in the Portuguese infrastructure were considered);
- The WEEE collected in the island territories of Portugal (Azores and Madeira) was processed primarily by the local operators. Two exceptions were considered: for WEEE of treatment categories B, D and E, which the local operators are not capable of processing, and for the amounts of WEEE that exceeded the locally installed processing capacity; in both cases it was considered that the WEEE was transported to the port of Lisbon in the Continental territory of Portugal and from here to an operator where it was processed; and
- All operations upstream of the WEEE processing operators were excluded from the calculations, including the logistics of WEEE collection.

4.2.3 Amounts of WEEE to be processed between 2012 and 2016

After a period from 2006 to 2011 during which two PRO's were licensed by the Portuguese government to develop the WEEE take back system and fulfil specific targets for WEEE treatment and recovery, the year of 2012 presented the prospect of a second 5 year period of activity of both organization, with increased challenges in the management of WEEE. The two PRO's have submitted applications to the government authorities soliciting new licenses. In this context, the improvement of the performance of WEEE treatment and recovery was made for a five year period, to coincide with the expected time during which the PRO's will continue to be responsible for the WEEE take back system in Portugal.

In order to improve the performance of WEEE treatment and recovery the expected amounts of WEEE to be collected and processed in the Portuguese infrastructure in the near future were calculated.

As the evolution of the scientific knowledge developed the systemic understanding over the waste management and the sustainable use of resources (adapted from Ribeiro, 2008) the correlation between the average life time of products and materials in the economy together with other factors has been demonstrated to play an important part in determining the amounts of waste generated. In the case of WEEE this is very relevant because the electrical and electronic equipment are durable goods, with relatively high average life times. Table 4.8 presents some examples that show the disparity in the average life time of different types of electrical and electronic equipment.

Table 4.8 – Range of average life times of electrical and electronic equipment (NIES, 2011)

Types of EEE	Minimum average life time (years)	Maximum average life time (years)
Large household appliances	6.6	12.3
Small household appliances	4.0	8.1
IT and telecommunications equipment	1.9	6.0
Consumer equipment	4.9	9.4
Lighting equipment	10.0	10.0
Electrical and electronic tools	1.0	12.5
Toys, leisure and sports equipment	7.0	10.6
Medical devices	4.0	4.0
Monitoring and control instruments	12.4	12.4
Automatic dispensers	9.0	9.0

The relatively high average life times of EEE mean that the WEEE being collected and processed in the present is the result of electrical and electronic equipment placed on the market in a significant number of previous years. In order to have the time differences of placement on the

market and generation of waste incorporated in the calculation, dynamic models were used, that consider the stock of products in the economy. In the research, the calculation of the WEEE amounts for the period of 2012 to 2016 in Portugal, was done using the model by Elshkaki *et al.* (2005) reformulated by Domingos (2008) (see Annex III).

In brief, the calculation considered the sales volumes of EEE in Portugal since 1994 (Luízio, 2004 and AMB3E, 2006, 2007, 2008, 2009, 2010 and 2011) of the different product types and the respective average life times to calculate the amount of WEEE generated between 2012 and 2016. Table 4.9 presents the respective amounts.

Table 4.9 – Amounts of WEEE generated in Portugal between 2012 and 2016

Treatment category	2012 (t)	2013 (t)	2014 (t)	2015 (t)	2016 (t)
Large household appliances (A)	47316.8	49254.5	50768.2	51926.6	52811.7
Cooling and freezing appliances (B)	34372.7	35872.6	37074.4	38024.1	38777.6
Small domestic appliances (C)	39235.9	42483.6	45145.6	47266.6	48908.1
Gas discharge lamps (D)	967.4	1107.9	1235.9	1350.3	1452.7
CRT televisions and monitors (E)	25443.5	24715.0	23654.4	22362.6	20962.0
Total	**147336.3**	**153433.6**	**157878.5**	**160930.3**	**162912.2**

Notes: Calculated based on the sales of EEE in Portugal (ANREEE, 2007 to 2012), considering the average life time of equipment (NIES, 2011).

According with the WEEE Directive and the recent WEEE Recast, a minimum collection rate of WEEE is established as follows:

- Until 31st of December 2015: 4 kilogram per inhabitant per year of WEEE from households (or the same amount of weight of WEEE as was collected on average in the three preceding years, whichever is greater);
- From 1st of January 2016 until 31st of December 2018: 45% of the average annual weight of EEE placed on the market during the three preceding years, of WEEE from households and professional activities.

The amounts of WEEE respective of the collection rate were calculated. Following the legal collection targets, in the first case, the current average amount of WEEE collected in the previous three years and the prospected evolution of the Portuguese population were considered (INE, 2011) and in the second case the prospect sales of EEE in Portugal were calculated based on the historical evolution.

The results showed that the collection target by 2016 represents an increase of more than 65% relative to the current collection target, applicable until 2015. Such an increase in collection by is certainly difficult to achieve the WEEE management systems from one year to the next. A more realistic approach was considered under which the PRO's in Portugal would increase the

amounts of WEEE collected progressively from 2012 to 2016. In this context, it was assumed that the amounts of collected WEEE will evolve linearly from the minimum amount in 2012, respective of the current collection target, to the maximum amount in 2016, respective of the new and increased collection target.

Table 4.10 presents the summary of the annual amounts of WEEE to be collected in the Portuguese infrastructure until 2016.

Table 4.10 – Annual amounts of WEEE collected in the Portuguese infrastructure per treatment category until 2016

Treatment category	2012 (t)	2013 (t)	2014 (t)	2015 (t)	2016 (t)
Large household appliances (A)	18735.7	22614.0	26489.8	30401.5	34329.6
Cooling and freezing appliances (B)	9579.3	10960.5	12328.7	13686.2	15044.0
Small domestic appliances (C)	13509.1	15604.8	17692.2	19772.6	21853.2
Gas discharge lamps (D)	591.4	698.5	862.0	1034.4	1189.2
CRT televisions and monitors (E)	6589.6	7183.6	7745.0	8279.2	8814.2
Total	**49005.0**	**57061.3**	**65117.6**	**73173.9**	**81230.2**

Notes: Calculated based on the sales of EEE in Portugal (ANREEE, 2007 to 2012), considering the average life time of equipment (NIES, 2011), historic collection data in Portugal per treatment category (AMB3E, 2006 to 2012 and ERP Portugal 2009 and 2010) and the legal targets (WEEE Recast).

The amounts of WEEE being generated and collected in the island territories of Portugal, Azores and Madeira, represent respectively 1.2% and 1.3% of the total amounts.

4.3 Improved WEEE treatment and recovery between 2012 and 2016

WEEE is processed in five distinct treatment categories which can be improved independently. In this context the improved performance was calculated using the different scenarios for each category of WEEE for a prospected period of 5 years of activity, between 2012 and 2016.

In the following sections, the results are presented individually for each of the five WEEE categories and the respective performance is assessed in the technical (reuse/recycling and recovery), economic (economic balance) and environmental (environmental balance) aspects.

The results are presented in absolute values and in specific values, per ton of input WEEE, for the year 2012 and cumulatively for the 5 year period between 2012 and 2016. The improved results are compared with the results of the reference *status quo* situation.

4.3.1 Large household appliances

The improvement of the treatment and recovery of large household appliances was done by recalculating the allocation of the amounts of WEEE collected from 2012 to 2016 by the 19 operators in the Portuguese infrastructure. This was done considering the individual processing capacity of the operators and the rules defined for each improvement scenario.

As an example, Figure 4.3 presents the amounts of WEEE allocated per operator in the Portuguese infrastructure for the year 2012, in each of the improvement scenarios. There is significant variation in the amounts allocated in the different scenarios and in particular, in scenarios #1 and #3, there is even amounts of WEEE that are not allocated. In these cases, it would not be necessary to recover the total amounts of WEEE to fulfil the designated objectives in the given scenarios (i.e. to achieve the minimum legal targets on reuse/recycling and recovery).

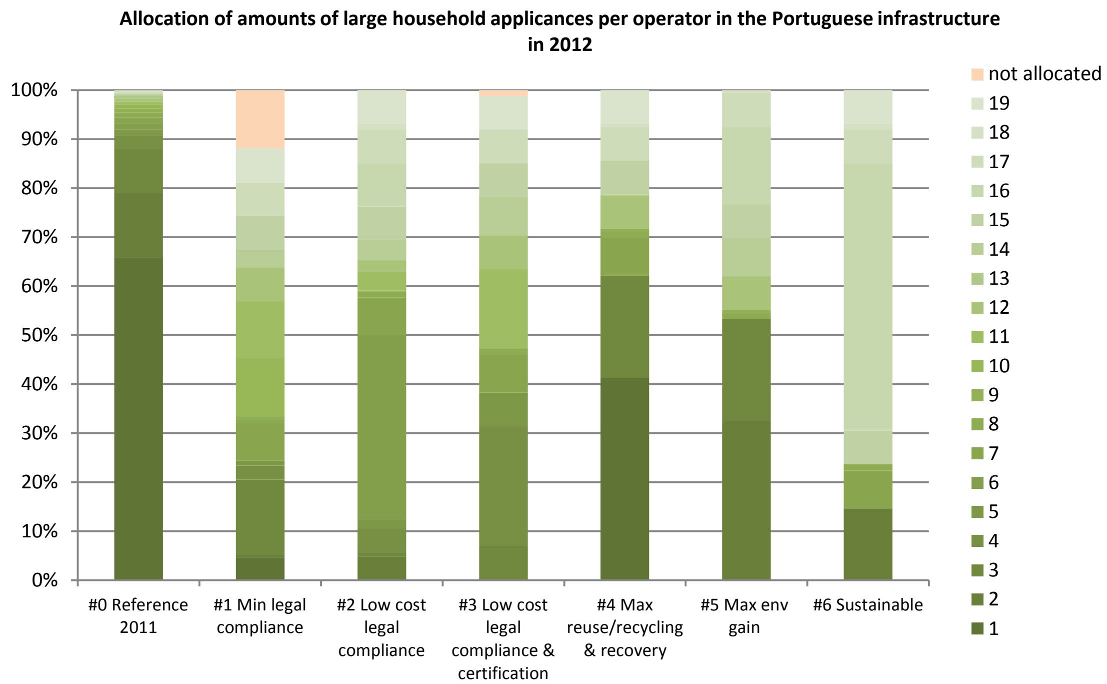
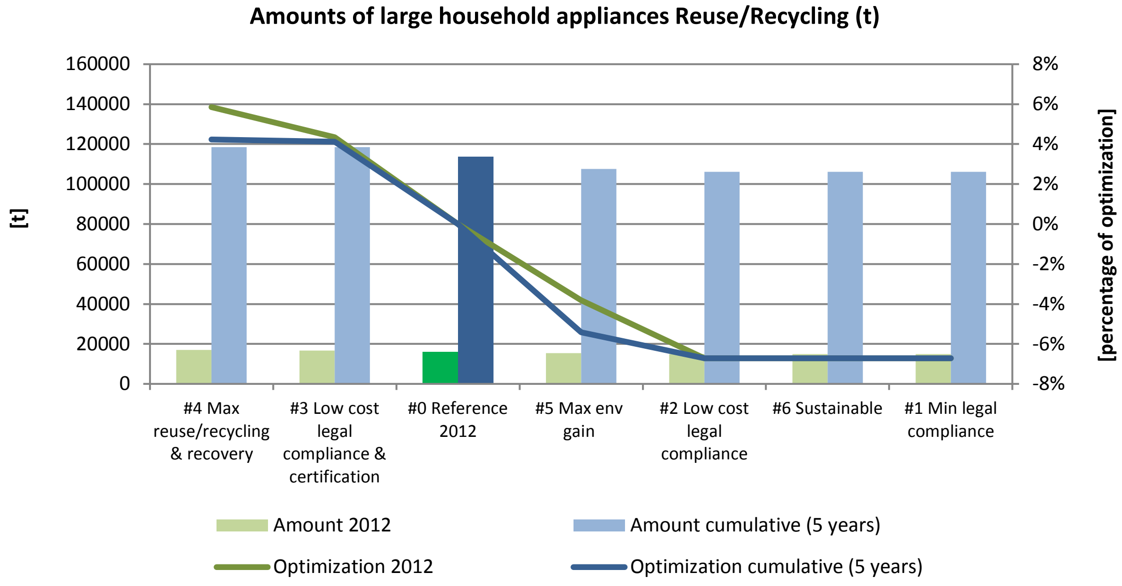


Figure 4.3 – Allocation of amounts of large household appliances per operator in the Portuguese infrastructure in 2012 (calculated)

4.3.1.1 Technical performance

Regarding the technical performance, two indicators are assessed: the reuse/recycling and the recovery of WEEE. Figure 4.4 presents the amounts of WEEE reuse/recycling in the Portuguese infrastructure in the different improvement scenarios. The reference performance scenario #0 is identified in darker colours and on the left side are the scenarios that present an increase in the performance, while on the right the scenarios that represent a decrease.

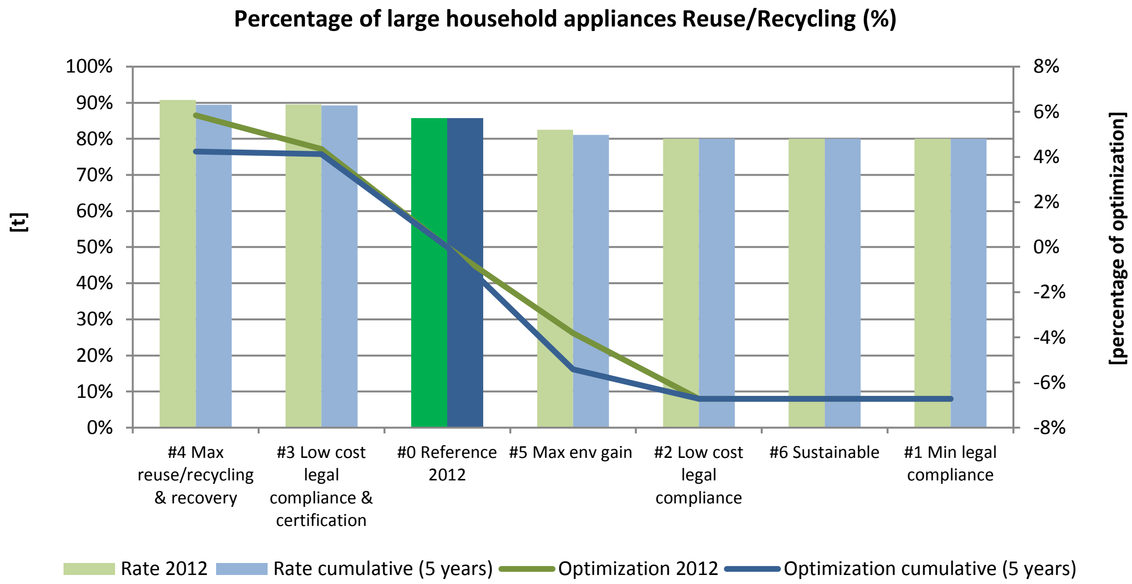


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.4 – Amounts of large household appliances Reuse/Recycling in the Portuguese infrastructure

In scenarios #4 and #5 there is an improvement between 4% and 6% on the amount of WEEE reuse/recycling compared to the reference performance scenario #0. The results in Figure 4.5 are identical for the specific values, in percentage of reuse/recycling per ton of input WEEE.

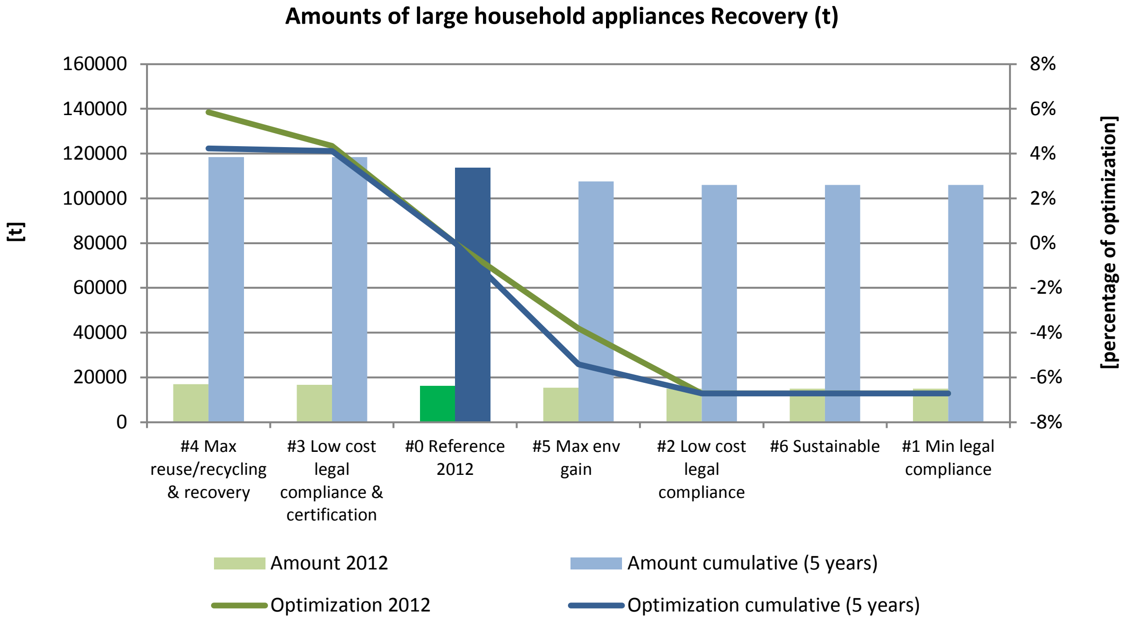
In the remaining scenarios on the right side of scenario #0 there is a decrease in the current performance level.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

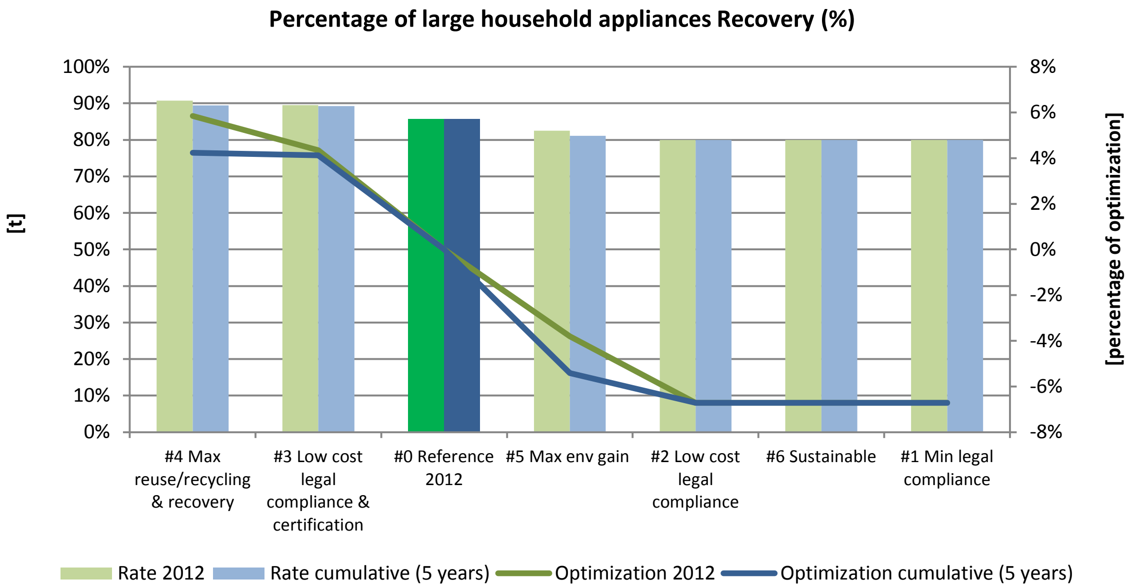
Figure 4.5 – Percentage of large household appliances Reuse/Recycling in the Portuguese infrastructure

Figure 4.6 and Figure 4.7 present the results for WEEE recovery which are very similar to the reuse/recycling.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.6 – Amounts of large household appliances Recovery in the Portuguese infrastructure



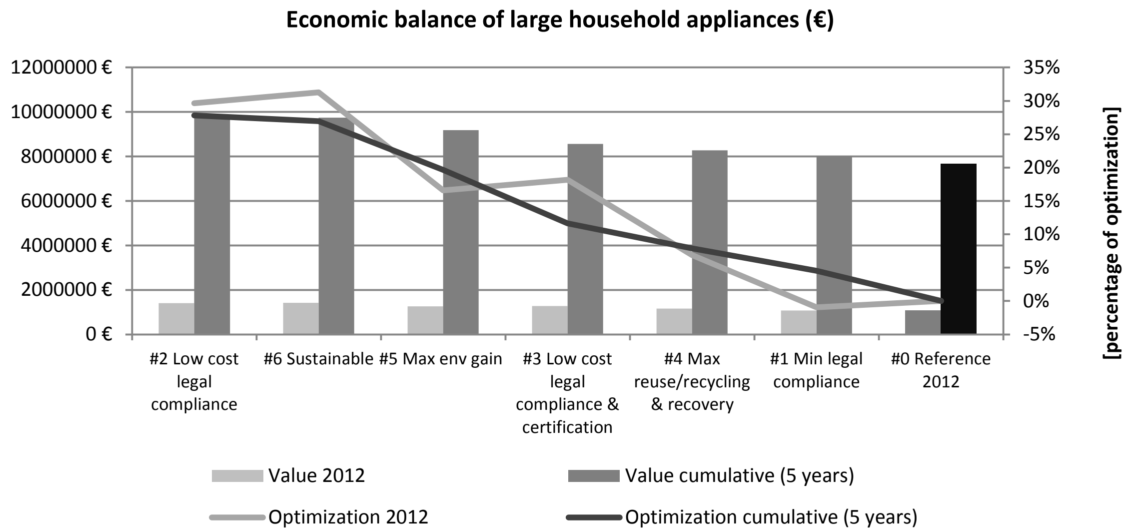
Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.7 – Percentage of large household appliances Recovery in the Portuguese infrastructure

4.3.1.2 Economic performance

The results of the improvement of the economic performance indicate that in all scenarios the economic balance of WEEE processing is increased from the current performance level.

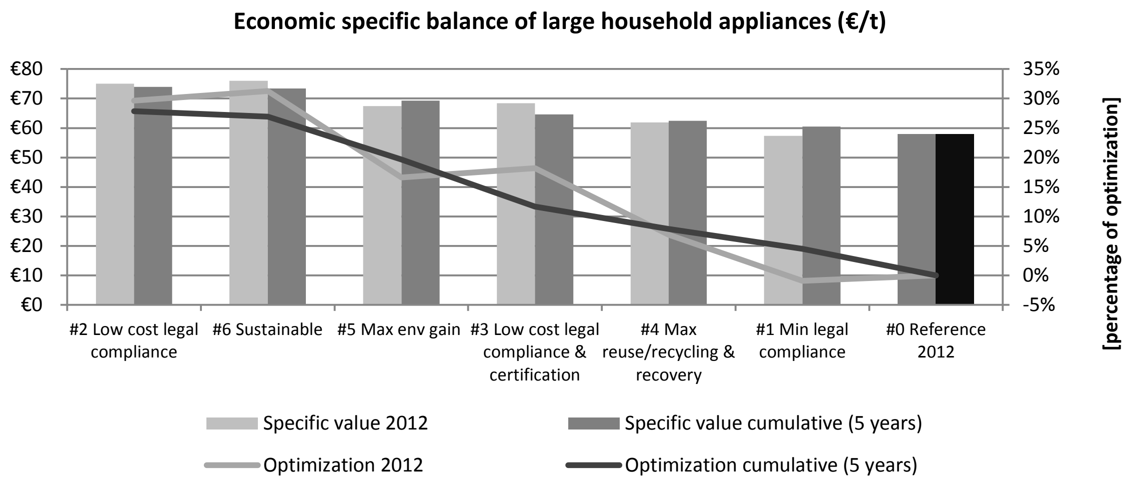
Figure 4.8 and Figure 4.9 present the economic balance of processing large household appliances in the Portuguese infrastructure, respectively in absolute and specific values. In darker colours the results of the reference performance scenario are presented.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.8 – Economic balance of large household appliances in the Portuguese infrastructure

The economic balance of treatment and recovery of large household appliances is positive with revenue surpassing the cost, considering the entire WEEE processing chain.



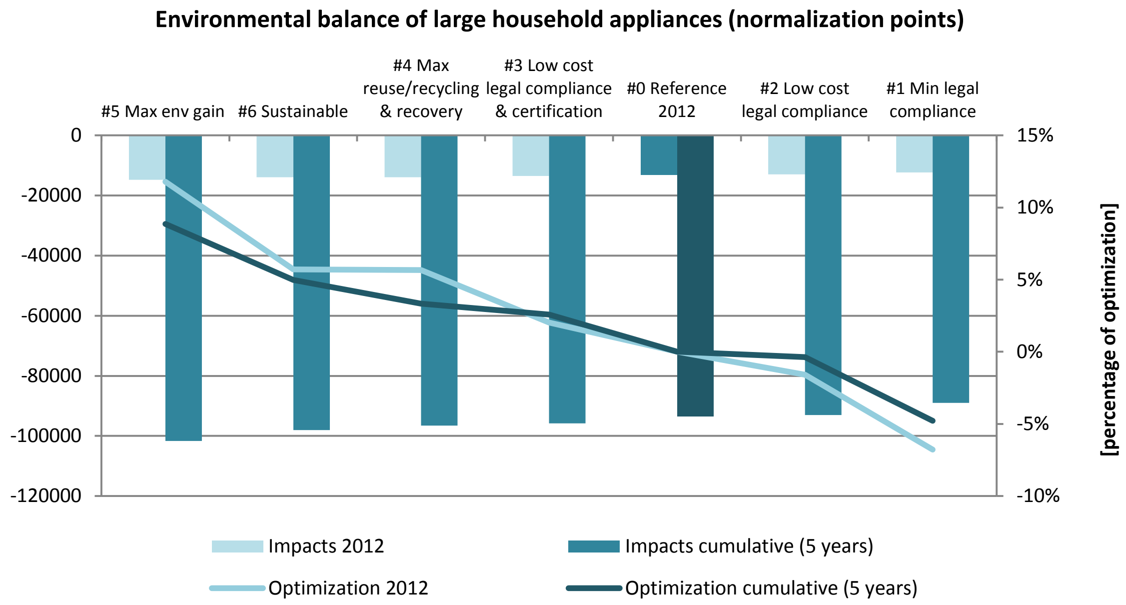
Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.9 – Economic specific balance of large household appliances in the Portuguese infrastructure

These results indicate that, in theory, it would not be necessary for PRO's to provide financial assistance for the operators to process large household appliances, as the activities of treatment and recovery along the entire end-of-life processing chain generates revenue that are higher that the respective costs. However, in practice the economic value of WEEE processing may not be evenly distributed through the different processing levels which mean that some operators may have negative economic balances. This is especially relevant for first tier operators which are the ones with whom PRO's sign contracts.

4.3.1.3 Environmental performance

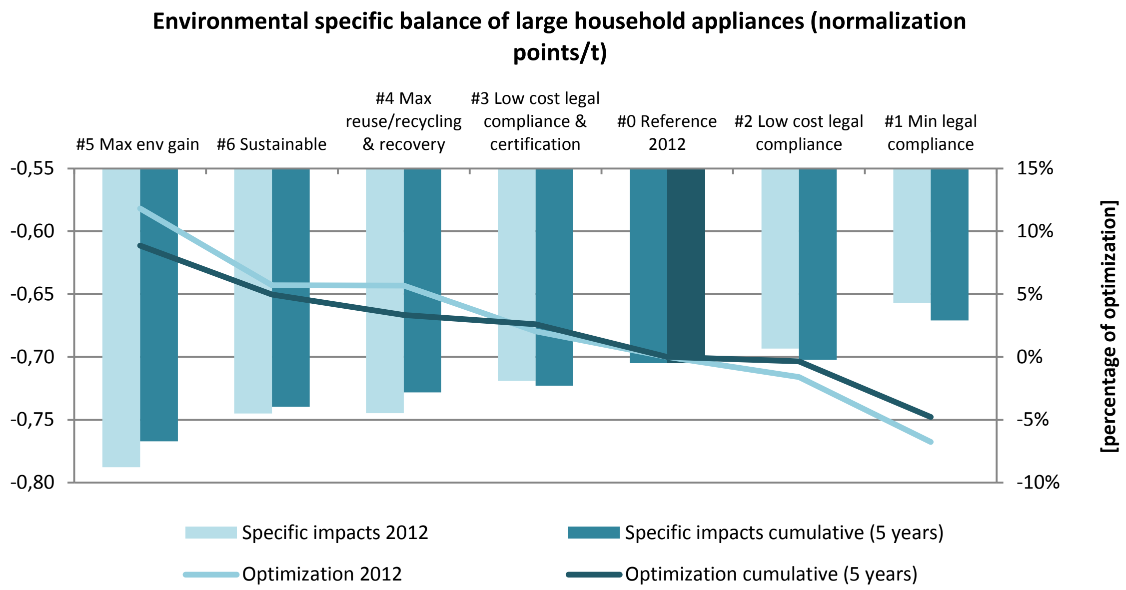
Regarding the environmental performance, the WEEE treatment and recovery represents an environmental gain. Figure 4.10 and Figure 4.11 present the environmental balance of processing large household appliances in the Portuguese infrastructure in the different scenarios of improvement (the negative values of environmental impacts represent avoided environmental impacts which can be considered as environmental gains). In darker colours the results of the reference performance scenario are presented.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.10 – Environmental balance of large household appliances in the Portuguese infrastructure

The results show that it is possible to improve from the current environmental performance level between 2% and 10% depending on the scenarios adopted to reallocate the WEEE amounts for processing in the Portuguese infrastructure.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.11 – Environmental specific balance of large household appliances in the Portuguese infrastructure

Overall, only scenarios #3 and #4 present improvements on the reference performance in all aspects, including technical, economic and environmental.

4.3.2 Cooling and freezing appliances

Cooling and freezing appliances are processed by three operators in the Portuguese infrastructure and include additional downstream processing stages and operators. The improvement was done by allocating the prospected amounts of WEEE to be processed until 2016 by the operators in the Portuguese infrastructure, considering the individual processing capacity and according with distinct rules and objectives established in the improvement scenarios.

Figure 4.12 presents one example of the allocation, per operator, of the amounts of WEEE collected in the Portuguese infrastructure in 2012 in the different improvement scenarios. In three of the scenarios, #1, #2 and #4, the allocation is very similar. Also in scenario #3 no amounts of WEEE are allocated. In this case, the operators are not able to fulfil the specific requirements of the scenario, which include that all of them are individually able to achieve the legal targets on recovery.

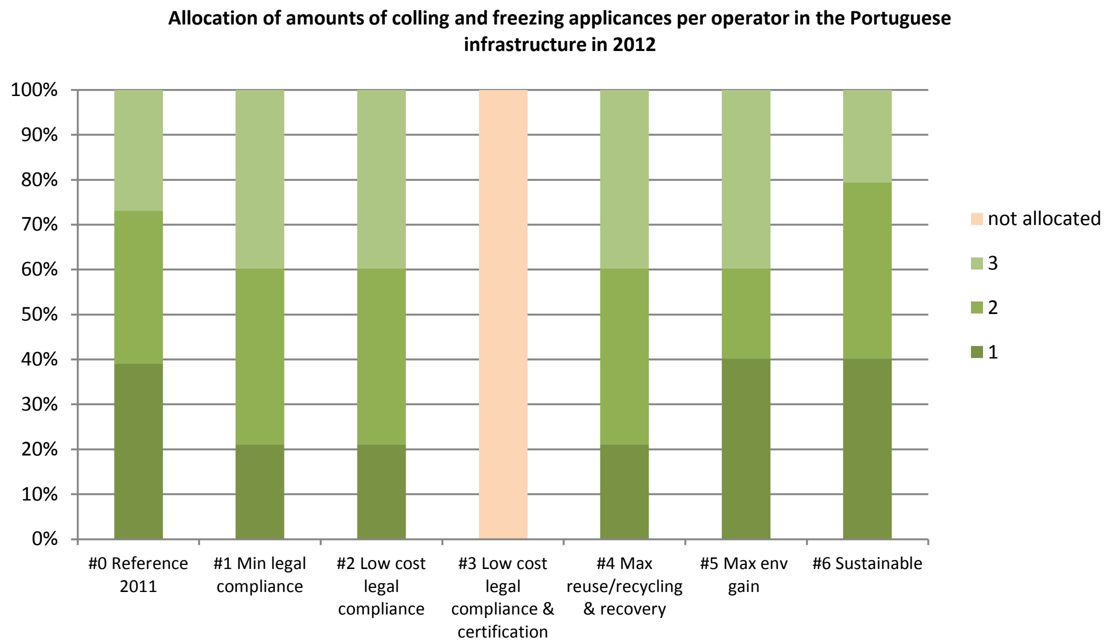


Figure 4.12 – Allocation of amounts of cooling and freezing appliances per operator in the Portuguese infrastructure in 2012 (calculated)

Based on the amounts of WEEE from treatment category B (Cooling and freezing appliances) to be processed, there will be a need to increase the processing capacity installed in the Portuguese infrastructure by the year 2014. Figure 4.13 presents the percentage of the amounts of WEEE to be processed that will be above the current installed capacity.

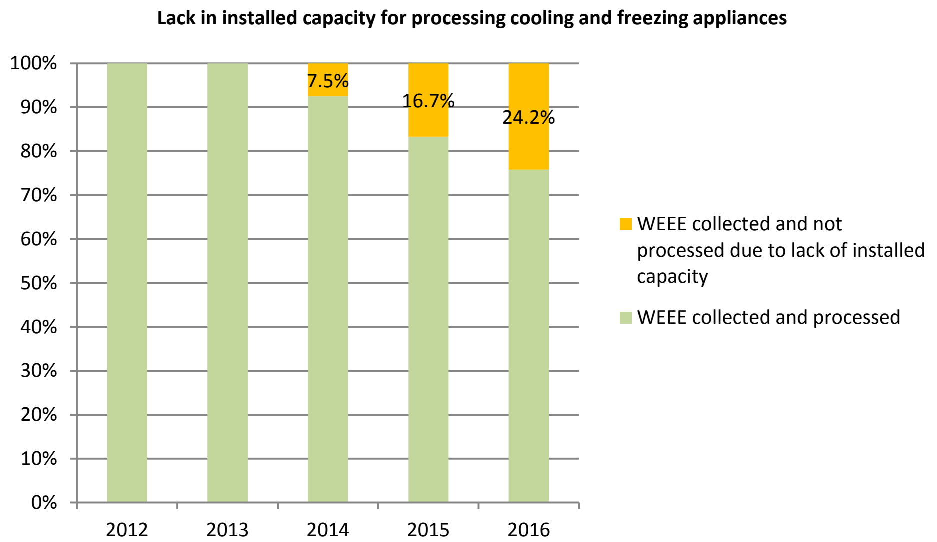


Figure 4.13 – Lack of installed capacity in the Portuguese infrastructure for processing cooling and freezing appliances

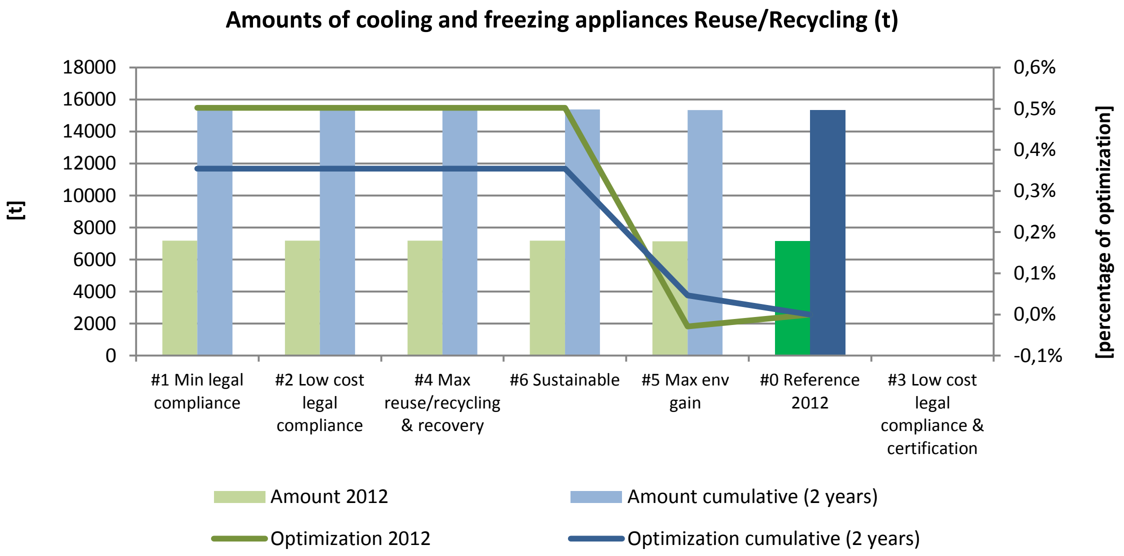
The results indicate that an increase in the processing capacity for cooling and freezing appliances is required to cope with the amounts of WEEE collection in the future. Given these limitations, for the purpose of the research work, the improvement of the treatment and recovery of cooling and freezing appliances in the Portuguese infrastructure was performed only to the years 2012 and 2013.

4.3.2.1 Technical performance

Regarding the technical performance of treatment and recovery of cooling and freezing appliances, the results indicate that the current performance of the Portuguese infrastructure can be improved slightly.

Figure 4.14 to Figure 4.17 present the results of reuse/recycling and recovery of cooling and freezing appliances for the different improvement scenarios. In scenario #3 the results are null because the Portuguese infrastructure is not able to satisfy the improvement requirements, namely associated with the certification of the operators.

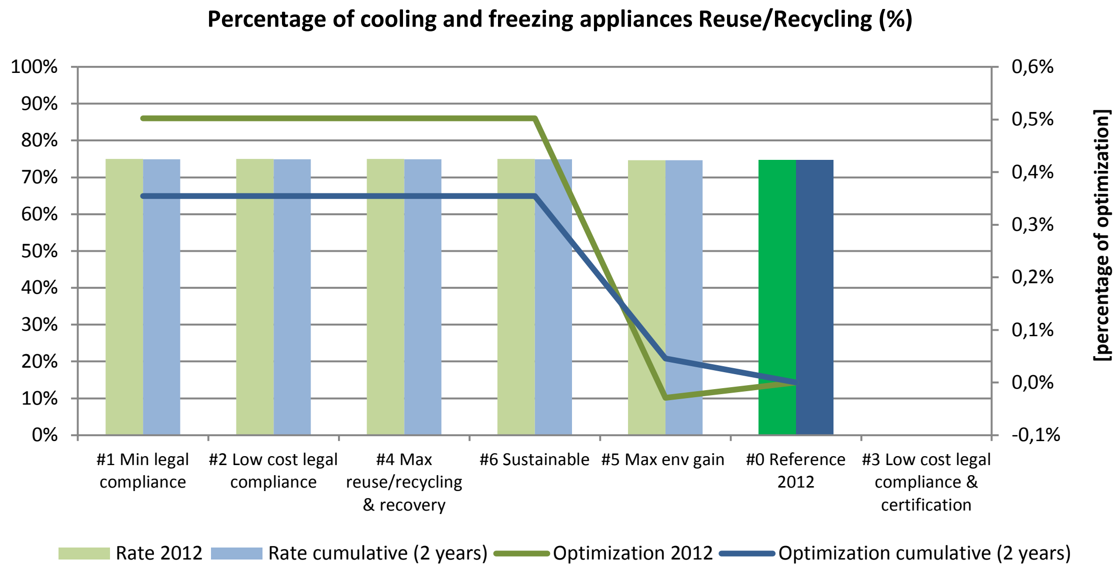
The results indicate that the improvement in the reuse/recycling and recovery of cooling and freezing appliances in the Portuguese infrastructure is only marginal, under 0.5% compared with the reference scenario. This is the direct consequence of all operators in the Portuguese infrastructure presenting homogeneous performance levels.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

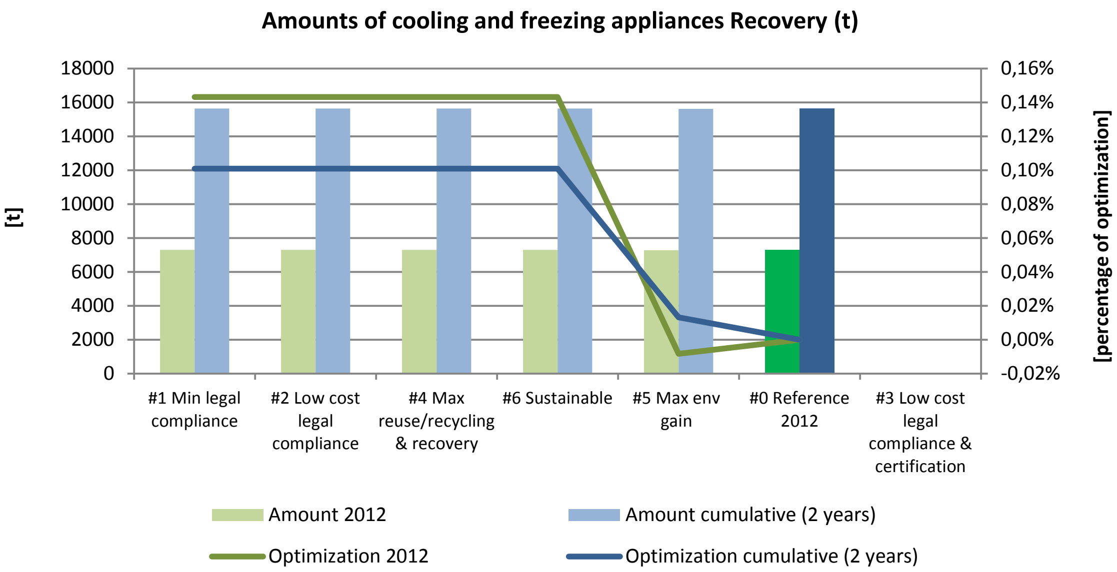
Figure 4.14 – Amounts of cooling and freezing appliances Reuse/Recycling in the Portuguese infrastructure

In the case of reuse/recycling the performance levels achieved in the Portuguese infrastructure are just above the current legal target defined in the WEEE Directive (75%). However, considering the increased targets of the WEEE Recast to enter in to force by 2016 (80%), it is clear that the current performance levels are not enough.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

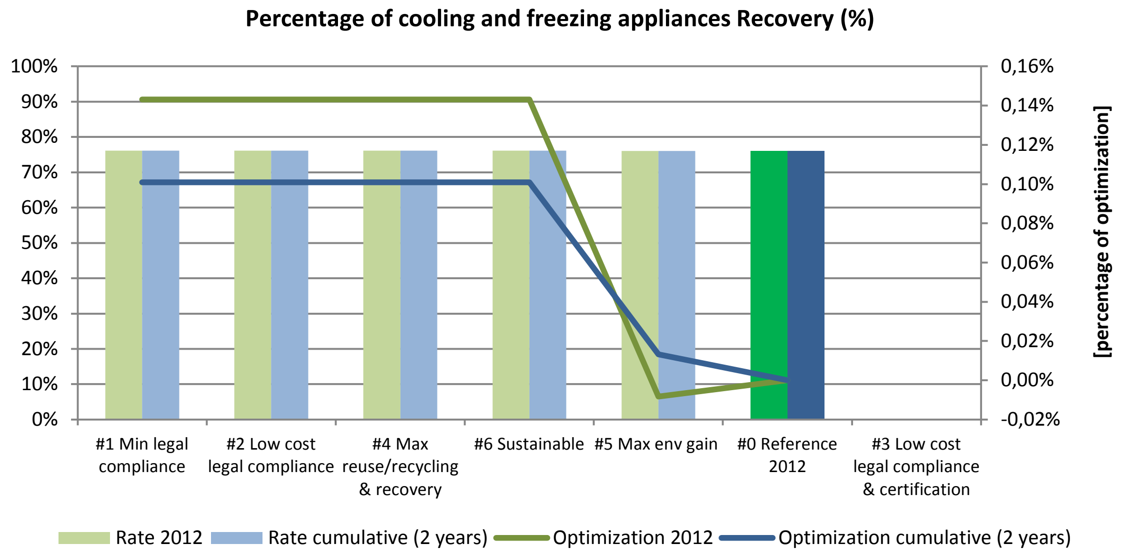
Figure 4.15 – Percentage of cooling and freezing appliances Reuse/Recycling in the Portuguese infrastructure



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.16 – Amounts of cooling and freezing appliances Recovery in the Portuguese infrastructure

More significant is the fact that the performance of recovery of cooling and freezing appliances in the Portuguese infrastructure, including the entire WEEE processing chain presented in Figure 4.17, does not achieve the minimum levels required to fulfil the current recovery targets defined in the WEEE Directive (80%). These results show the clear need to improve the recovery of cooling and freezing appliances processed in the Portuguese infrastructure.

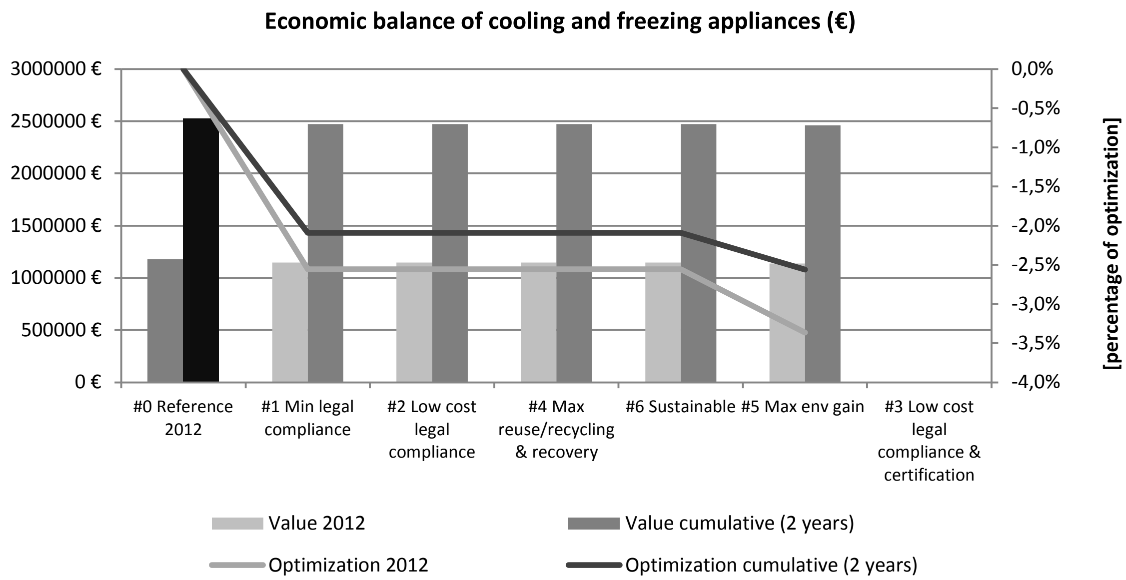


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.17 – Percentage of cooling and freezing appliances Recovery in the Portuguese infrastructure

4.3.2.2 Economic performance

The balance of the cost and revenue for treatment and recovery of cooling and freezing appliances in the Portuguese infrastructure including the entire WEEE processing chain in presented in Figure 4.18 and Figure 4.19.

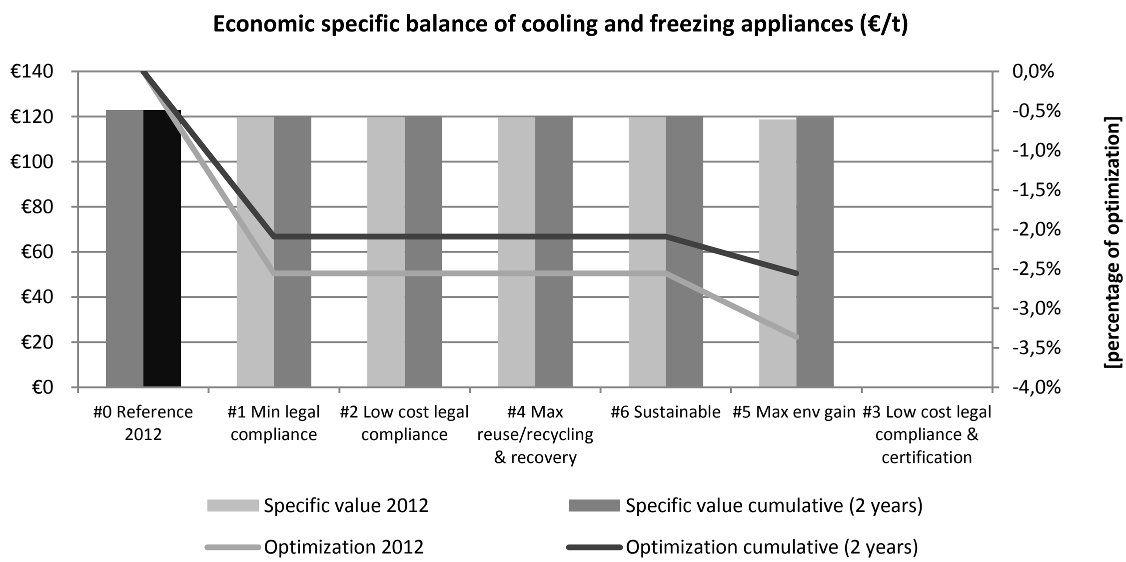


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.18 – Economic balance of cooling and freezing appliances in the Portuguese infrastructure

The results show that the reference performance levels are improved, considering the current conditions assessed in the research work, and that the processing of cooling and freezing appliances represents a positive economic value for the entire WEEE processing chain.

In theory, if the economic value was equally distributed along the entire WEEE processing chain, the results would indicate that the PRO's didn't need to provide financial assistance for the operators to ensure the treatment and recovery of cooling and freezing appliances.



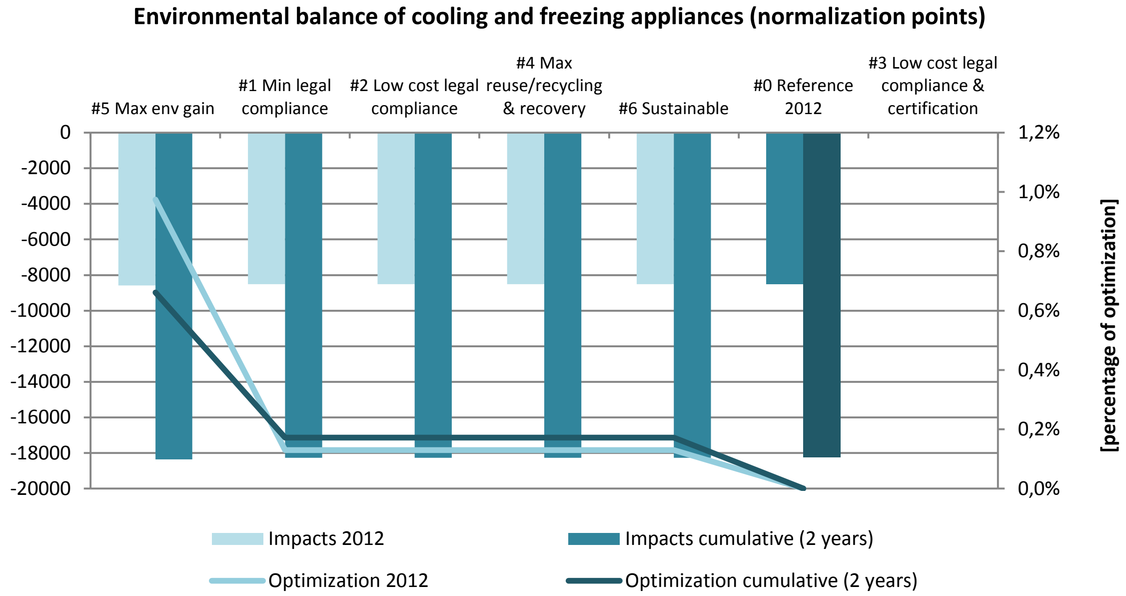
Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.19 – Economic specific balance of cooling and freezing appliances in the Portuguese infrastructure

4.3.2.3 Environmental performance

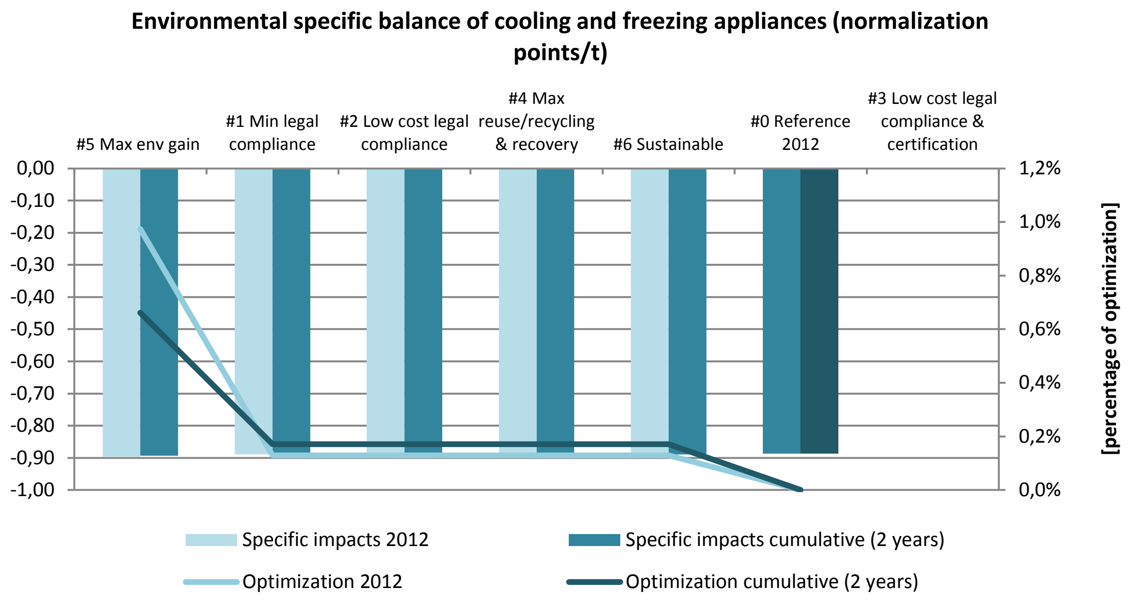
The balance of the environmental impacts of the treatment and recovery of cooling and freezing appliances in the Portuguese infrastructure presents a global negative value, which represents an environmental gain.

Figure 4.20 and Figure 4.21 present respectively the absolute and specific environmental balance of the treatment and recovery of cooling and freezing appliances. The results in both cases indicate that the environmental performance can be improved marginally, up to 1%, compared to the current performance levels. This is the consequence of the operators in the Portuguese infrastructure and the respective downstream operators presenting very similar environmental performances.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.20 – Environmental balance of cooling and freezing appliances in the Portuguese infrastructure



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.21 – Environmental specific balance of cooling and freezing appliances in the Portuguese infrastructure

With the exception of scenario #3, all improvement scenarios present improvements on the reference performance considering the technical and environmental aspects. Regarding the economic aspects, despite the reference scenario showing the best performance, all the other scenarios present a positive economic balance.

4.3.3 Small domestic appliances

The improvement of the treatment and recovery of small domestic appliances was done by recalculating the allocation of the amounts of WEEE to be processed until 2016 by each of the 18 operators in the Portuguese infrastructure. The individual processing capacity of the operators was considered, as well as the specific rules and objectives established in the improvement scenarios.

Figure 4.22 presents one example of the allocation, per operator, of the amounts of WEEE collected in the Portuguese infrastructure in 2012 in each of the improvement scenarios. In scenario #2 part of the amounts of WEEE are not allocated, as the remaining amount are sufficient to fulfil strictly the minimum legal requirements on reuse/recycling and recovery of WEEE.

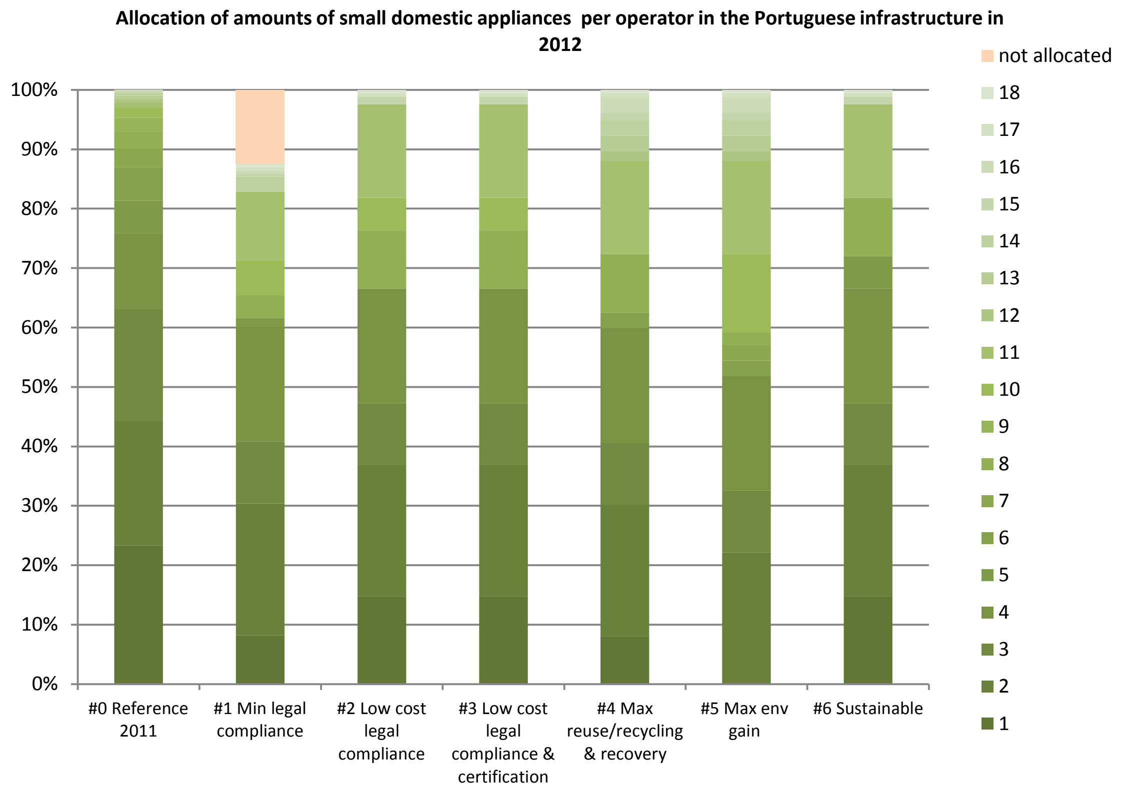


Figure 4.22 – Allocation of amounts of small domestic appliances per operator in the Portuguese infrastructure in 2012 (calculated)

Based on the amounts of WEEE to be processed from treatment category C (Small domestic appliances), there is a need to increase the current processing capacity installed in the Portuguese infrastructure by 2015. Figure 4.23 presents the percentage of the amounts of WEEE that will be above the current installed capacity.

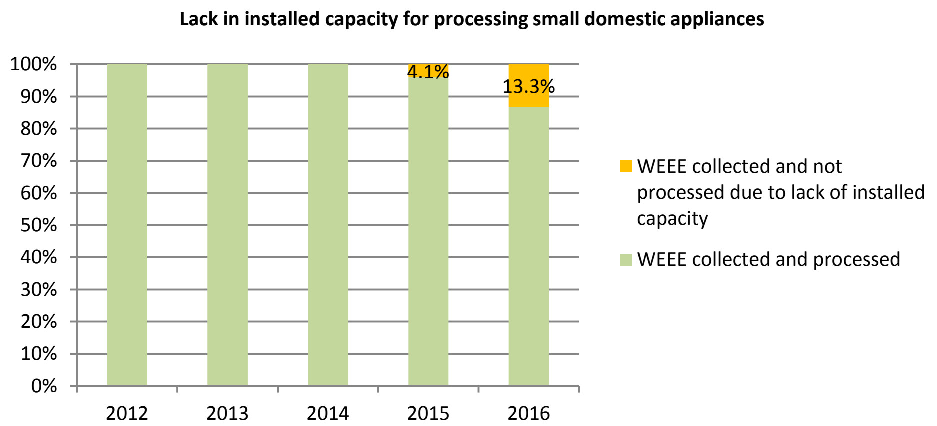


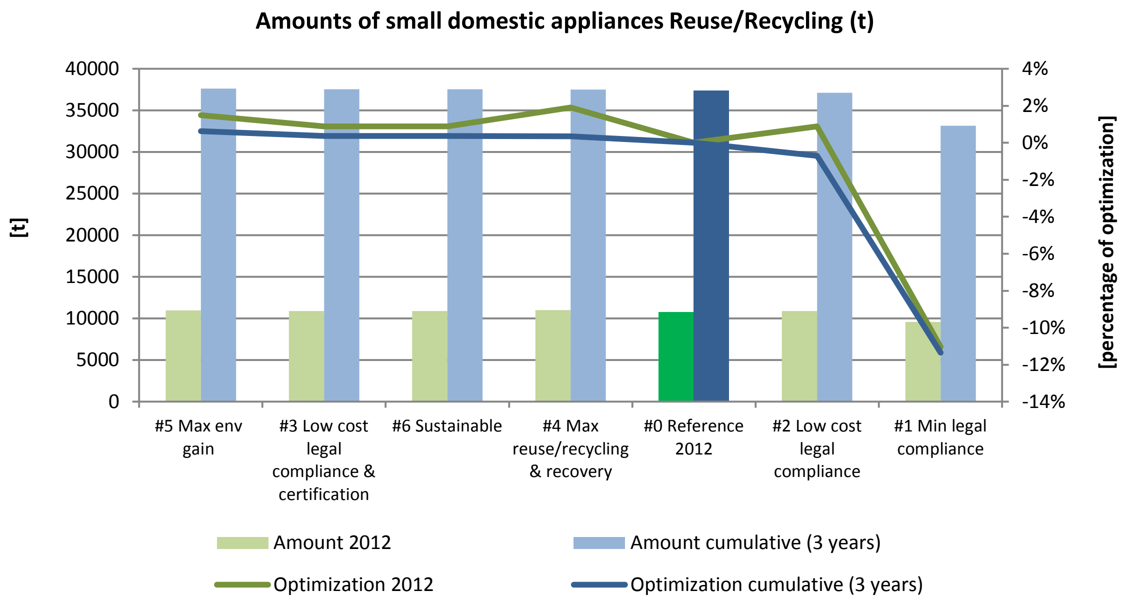
Figure 4.23 – Lack of installed capacity in the Portuguese infrastructure for processing small domestic appliances

Given the limitations of the processing capacity installed in the Portuguese infrastructure, for the purpose of the research work, the improvement of the treatment and recovery of small domestic appliances was performed only for the period from 2012 to 2014.

4.3.3.1 Technical performance

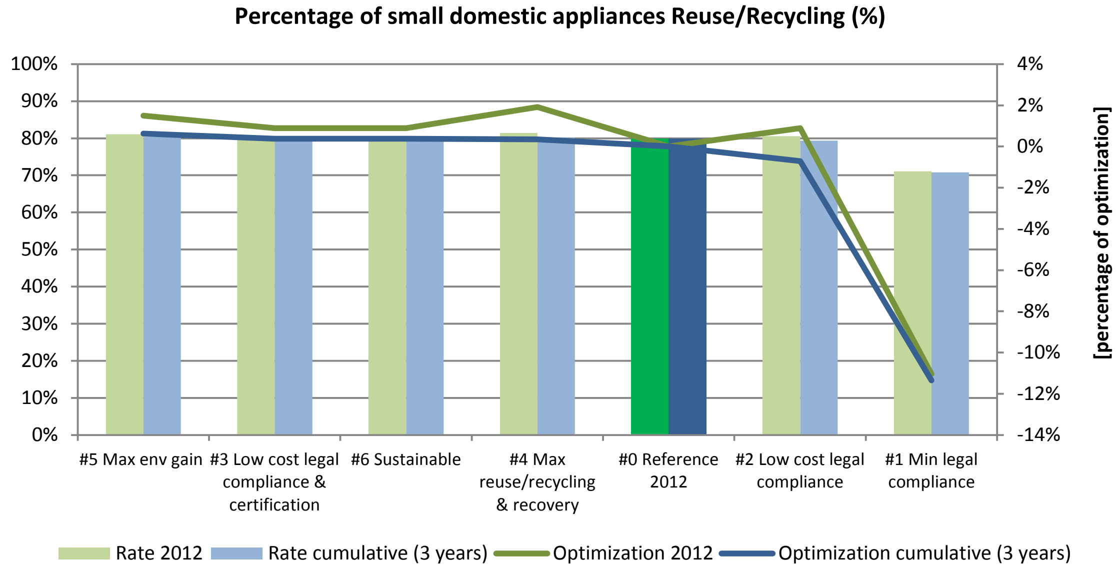
The technical performance of the treatment and recovery of small domestic appliances in the Portuguese infrastructure was assessed for different scenarios. Figure 4.24 and Figure 4.25 respectively present the amount and percentage of WEEE reuse/recycling.

It is possible to verify that the current performance can be improved up to 2%, but it can also be decreased by approximately 12% and still fulfil the reuse/recycling legal targets.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

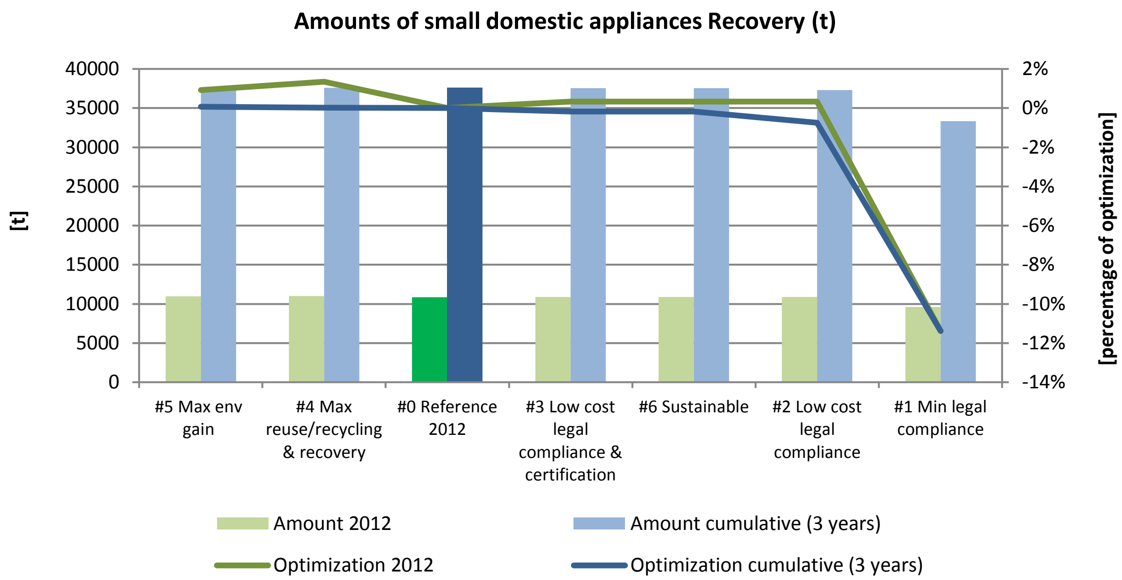
Figure 4.24 – Amounts of small domestic appliances Reuse/Recycling in the Portuguese infrastructure



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

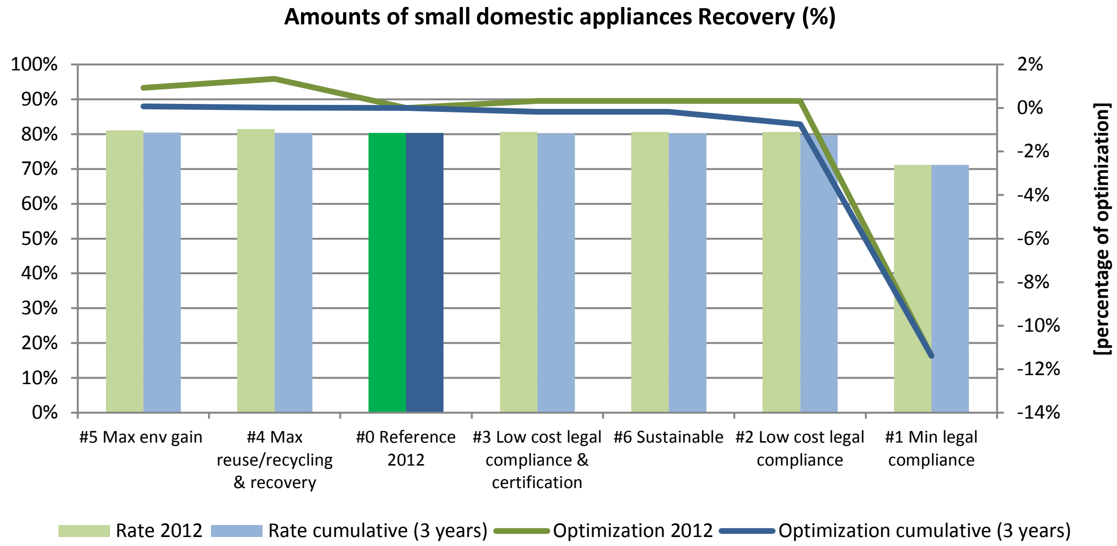
Figure 4.25 – Percentage of small domestic appliances Reuse/Recycling in the Portuguese infrastructure

Regarding the recovery of small domestic appliances, Figure 4.26 and Figure 4.27 show marginal improvements, fewer than 2%, for the Portuguese infrastructure. It is also possible to decrease the current performance by approximately 12% and maintain the fulfilment of the legal targets concerning the recovery of such WEEE.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.26 – Amounts of small domestic appliances Recovery in the Portuguese infrastructure

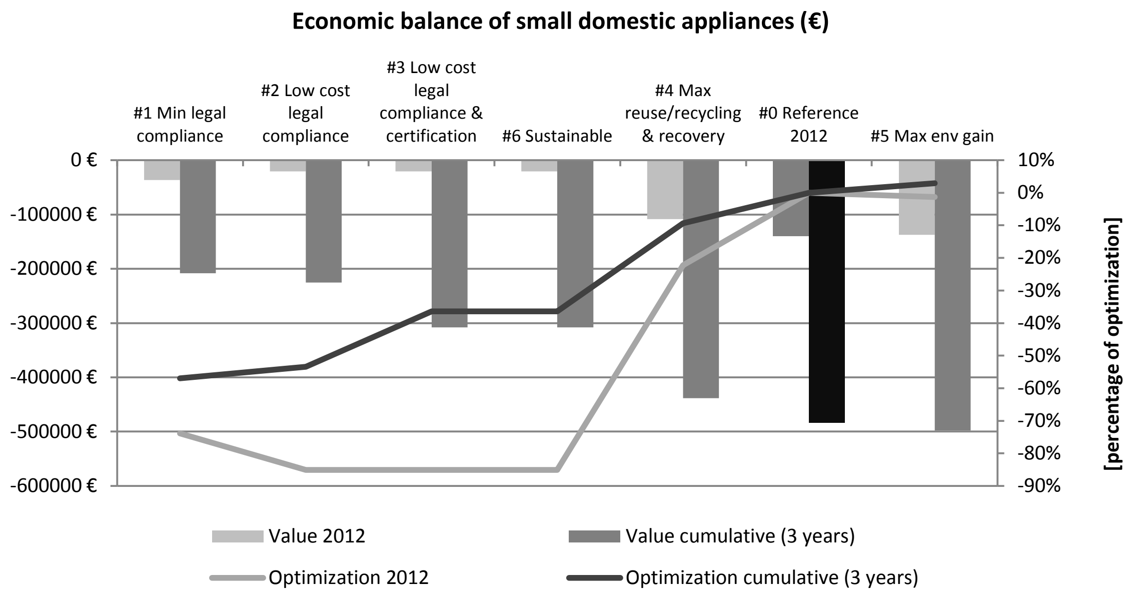


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.27 – Percentage of small domestic appliances Recovery in the Portuguese infrastructure

4.3.3.2 Economic performance

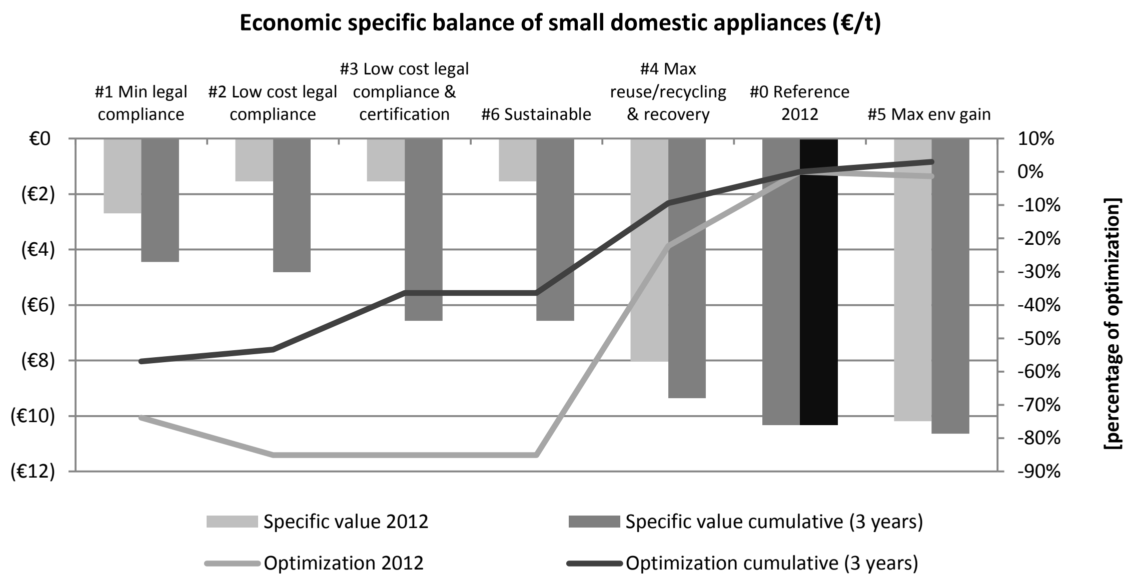
The economic balance of treatment and recovery of small domestic appliances in the Portuguese infrastructure, including the downstream operators along the entire WEEE processing chain, presents a negative value, as Figure 4.28 and Figure 4.29 show. The results indicate that the WEEE processing chain is not economically viable and requires financial input. This directly implicates the PRO's, as they are legally responsible to finance the WEEE treatment and recovery.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.28 – Economic balance of small domestic appliances in the Portuguese infrastructure

The results also show that it is possible to improve the current economic performance for small domestic appliances. The overall negative economic balance may be reduced up to 60% over a 3 year period.



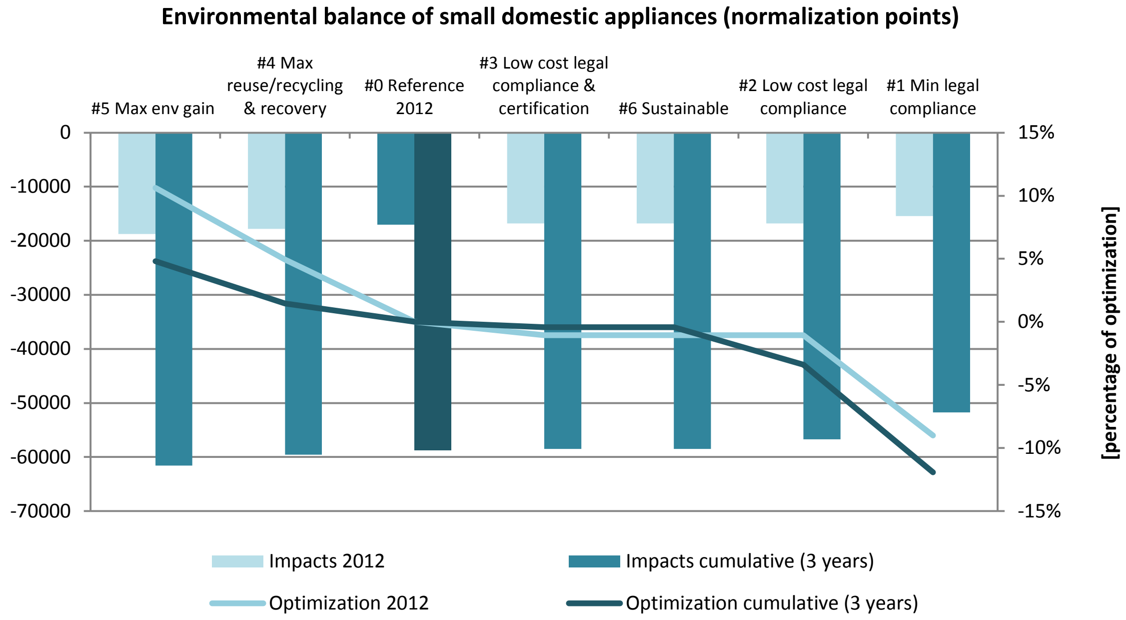
Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.29 – Economic specific balance of small domestic appliances in the Portuguese infrastructure

The results show that the PRO's have to provide financial assistance for operators to ensure the treatment and recovery of small domestic appliances and that such assistance can be significantly reduced compared to the reference levels.

4.3.3.3 Environmental performance

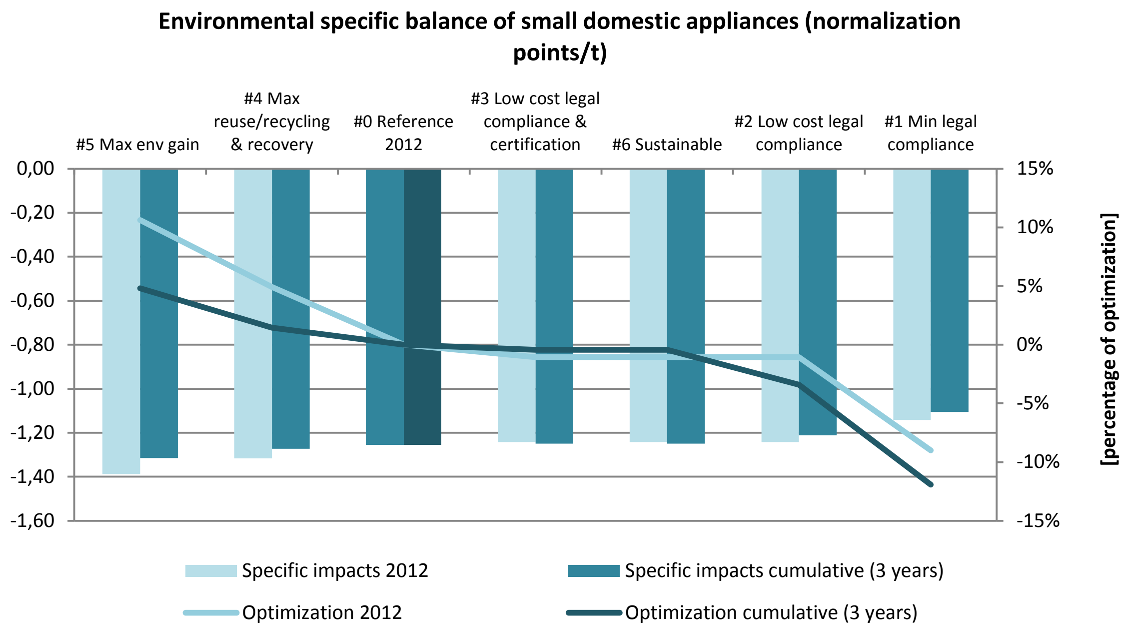
The treatment and recovery of small domestic appliances represents an environmental gain overall. The results of the improvement presented in Figure 4.30 and Figure 4.31 indicate that it can be improved by as much as 10% over a 3 year period.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.30 – Environmental balance of small domestic appliances in the Portuguese infrastructure

For the year 2012 alone, the improvements can reach as much as 5% in the current Portuguese infrastructure.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.31 – Environmental specific balance of small domestic appliances in the Portuguese infrastructure

Only scenario #4 presents improvements on the reference performance in all aspects, including technical, economic and environmental.

4.3.4 Gas discharge lamps

Gas discharge lamps are processed by 2 operators in the Portuguese infrastructure. The improvement of the current performance levels was assessed by allocating the prospect amounts of WEEE to be collected in Portugal between 2012 and 2016, according with different improvement scenarios. Figure 4.32 presents the allocation of the amounts of gas discharge lamps in the Portuguese infrastructure by 2012 in the different improvement scenarios.

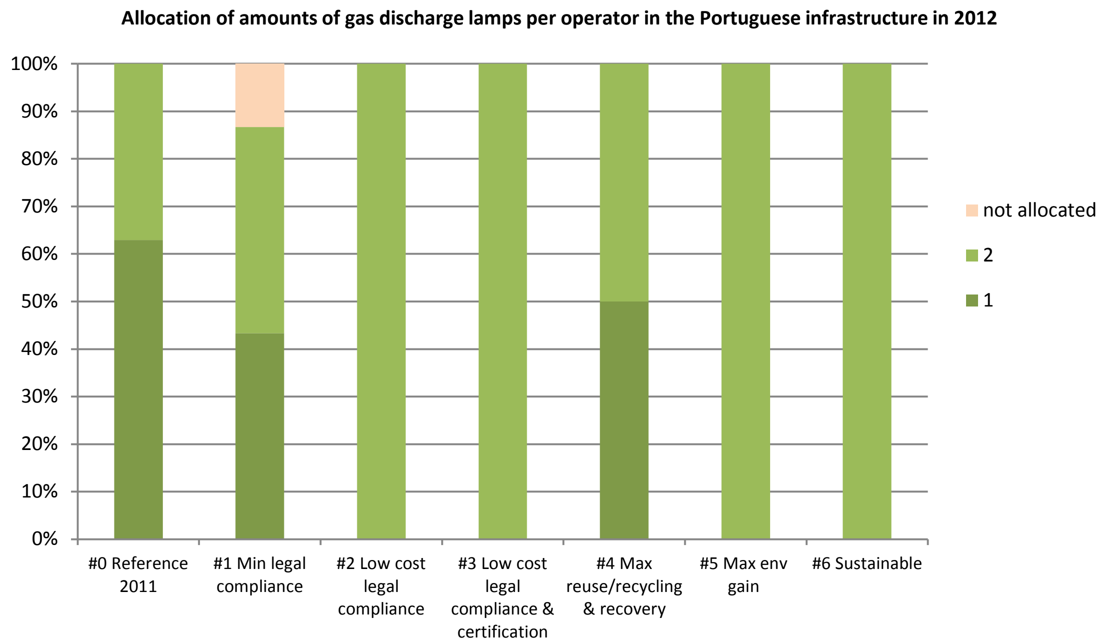


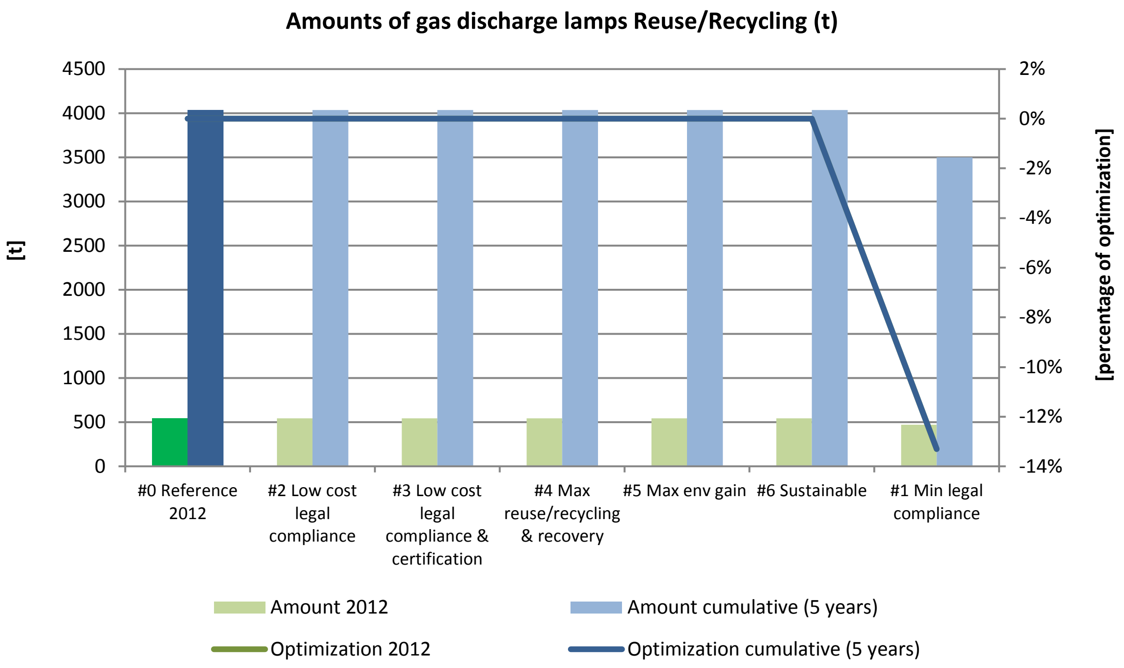
Figure 4.32 – Allocation of amounts of gas discharge lamps per operator in the Portuguese infrastructure in 2012 (calculated)

4.3.4.1 Technical performance

Regarding the technical performance of reuse/recycling and recovery of gas discharge lamps, the current performance of the Portuguese infrastructure including the entire WEEE processing chain is high and homogeneous considering each operator, as described in chapter 3.

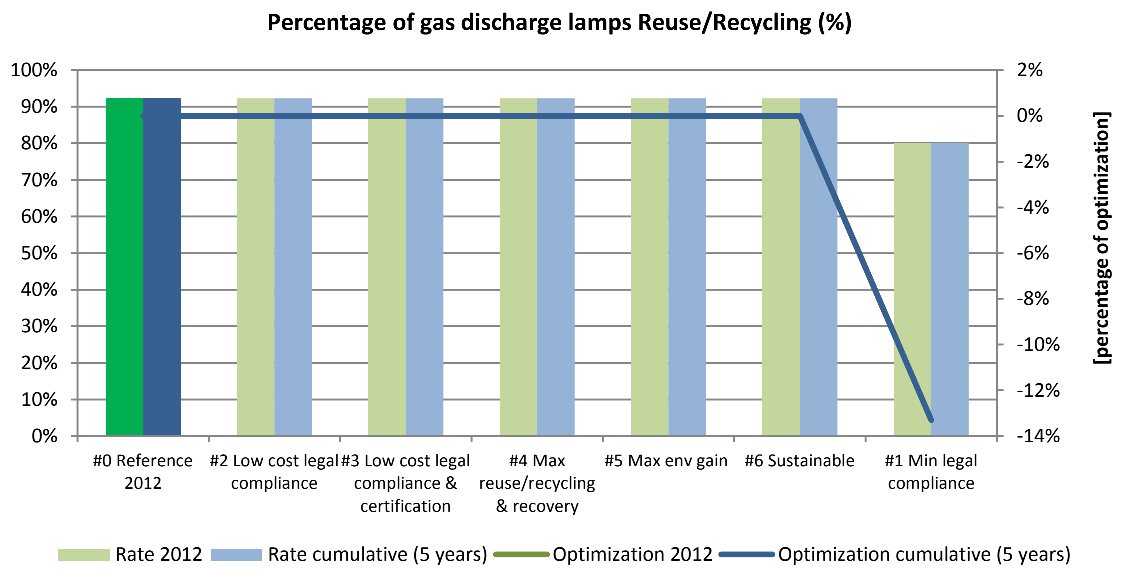
In this context, of all the different scenarios tested, the only differing result was related with the achievement of the strict minimum level necessary to fulfil the legal targets on reuse/recycling and recovery.

As Figure 4.33 and Figure 4.34 show, based on the current performance levels by the operators in the Portuguese infrastructure, it is possible to decrease the reuse/recycling of gas discharge lamps by approximately 13% and still be able to fulfil the respective legal targets.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

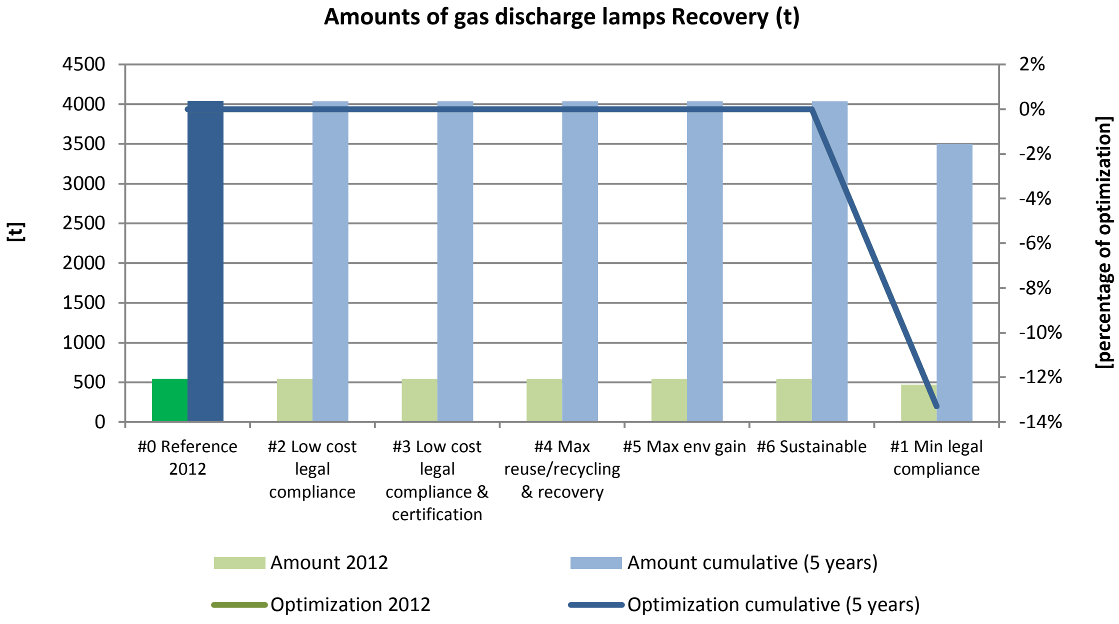
Figure 4.33 – Amounts of gas discharge lamps Reuse/Recycling in the Portuguese infrastructure



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

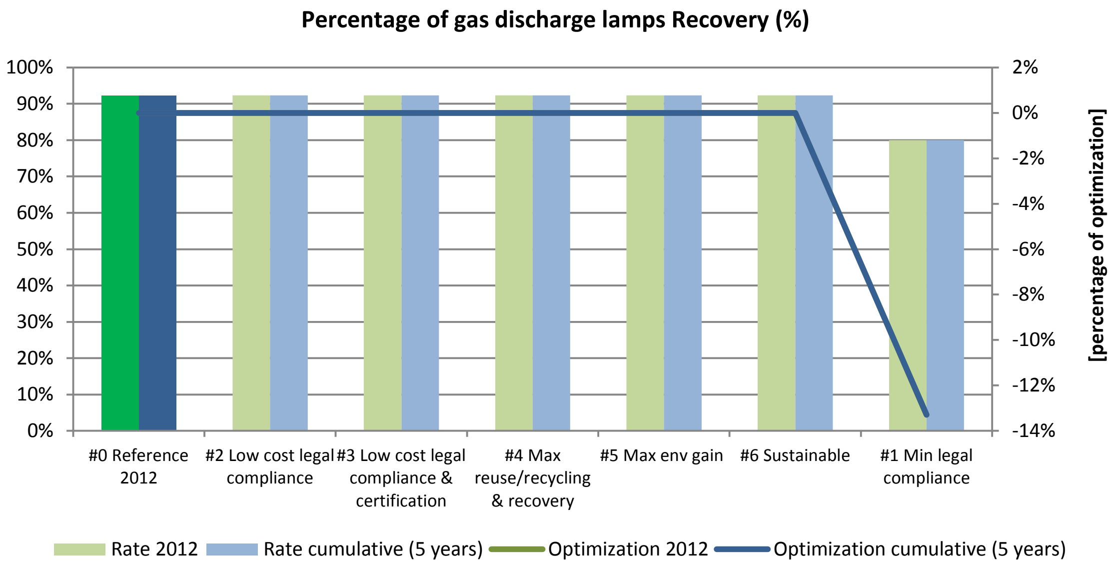
Figure 4.34 – Percentage of gas discharge lamps Reuse/Recycling in the Portuguese infrastructure

Regarding the recovery of gas discharge lamps the results are similar, as Figure 4.35 and Figure 4.36 show.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.35 – Amounts of gas discharge lamps Recovery in the Portuguese infrastructure

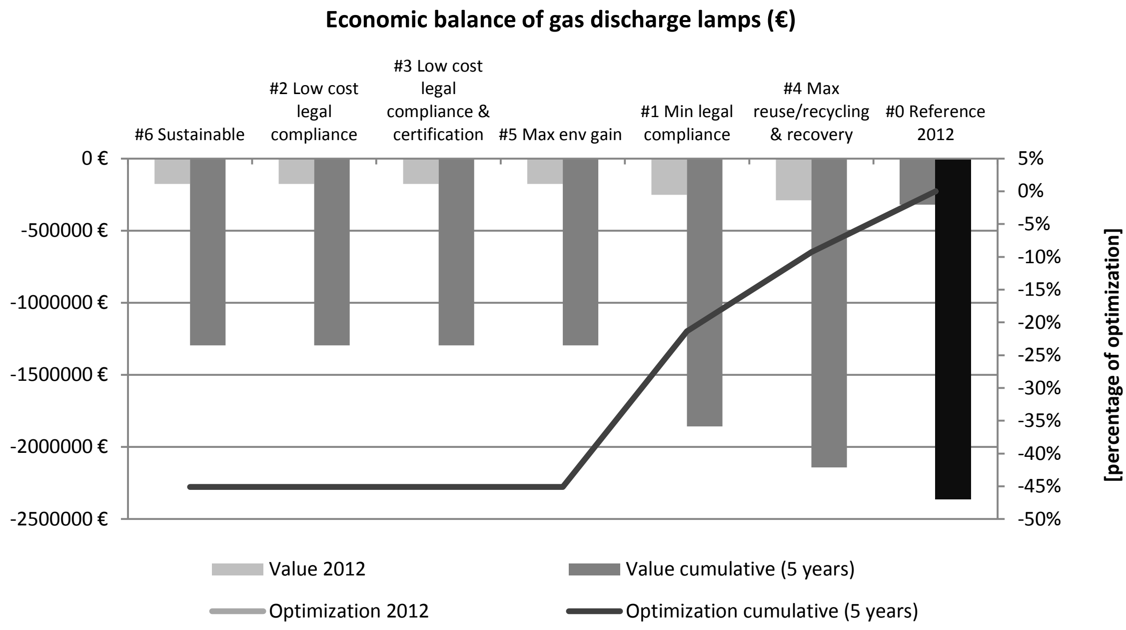


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.36 – Percentage of gas discharge lamps Recovery in the Portuguese infrastructure

4.3.4.2 Economic performance

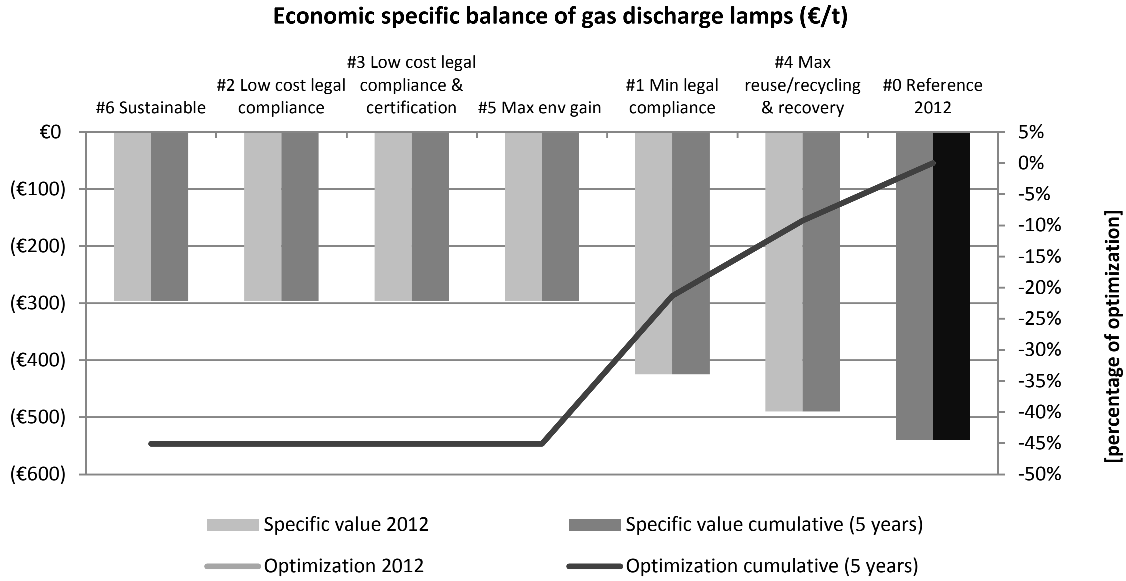
The economic balance of the treatment and recovery of gas discharge lamps presents a significant negative value. This means that the PRO's have to provide the financial assistance and thus fulfil the legal responsibilities in order to ensure the treatment and recovery of such WEEE.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.37 – Economic balance of gas discharge lamps in the Portuguese infrastructure

As Figure 4.37 and Figure 4.38 indicate, it is possible to improve the economic balance of the processing the gas discharge lamps in the Portuguese infrastructure, including the downstream processing and recovery, and reduce its negative value up to 45% over a 5 year period.

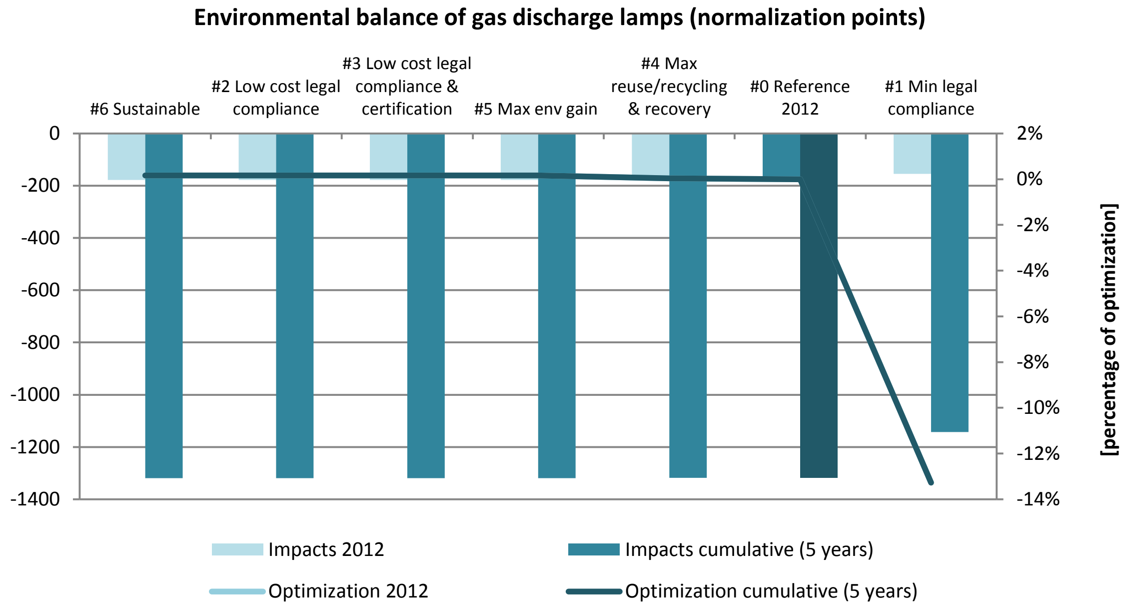


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.38 – Economic specific balance of gas discharge lamps in the Portuguese infrastructure

4.3.4.3 Environmental performance

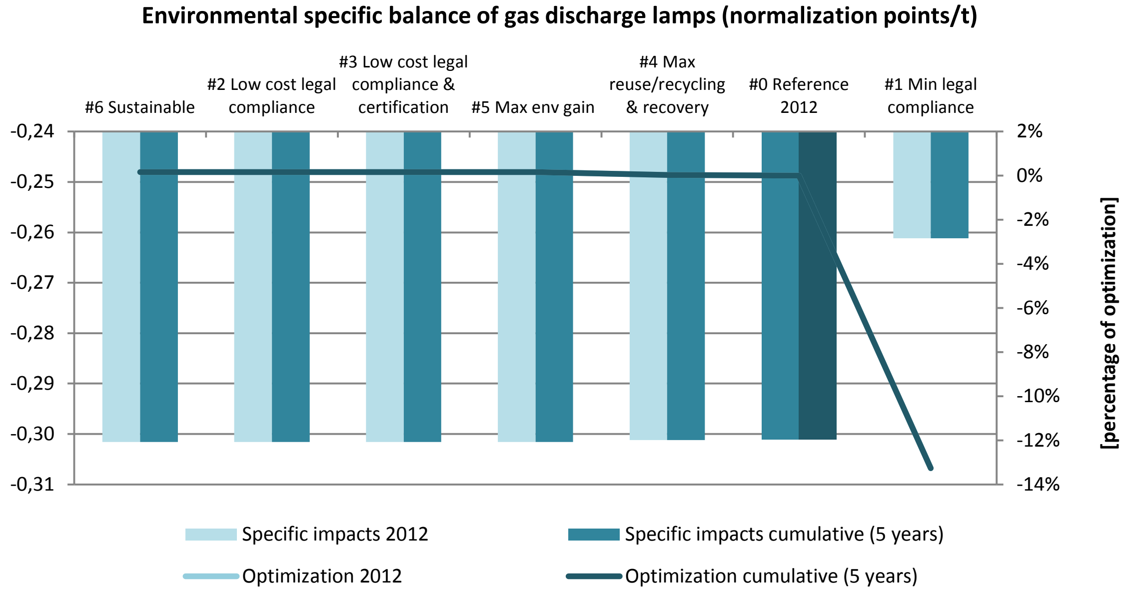
The treatment and recovery of lamps overall presents negative environmental impacts or environmental gain, as Figure 4.39 and Figure 4.40 show.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.39 – Environmental balance of gas discharge lamps in the Portuguese infrastructure

The results indicate that the environmental performance of the processing of gas discharge lamps in the Portuguese infrastructure can be only marginally improved, by less than 1%. It can also be decreased by approximately 13% if only the strict minimum legal requirements on treatment and recovery are met, as the results of scenario #1 indicate.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.40 – Environmental specific balance of gas discharge lamps in the Portuguese infrastructure

All scenarios except #1 present improvements on the reference performance considering the economic and environmental aspects. Regarding the technical performance, these scenarios were identical to the current performance level.

4.3.5 CRT televisions and monitors

For CRT televisions and monitors the Portuguese infrastructure includes 3 operators capable of processing it. The allocation of the WEEE amounts by the operators from 2012 to 2016 was calculated in the different scenarios and the respective performance levels were assessed.

Figure 4.41 presents an example of the allocation of the amounts of WEEE in the Portuguese infrastructure for the year 2012. No amounts of WEEE are allocated in scenario #3 as the operators are unable to fulfil the respective improvement rules, namely that all operators individually achieve the reuse/recycling and recovery legal targets in order to allow for the implementation of certified environmental management systems.

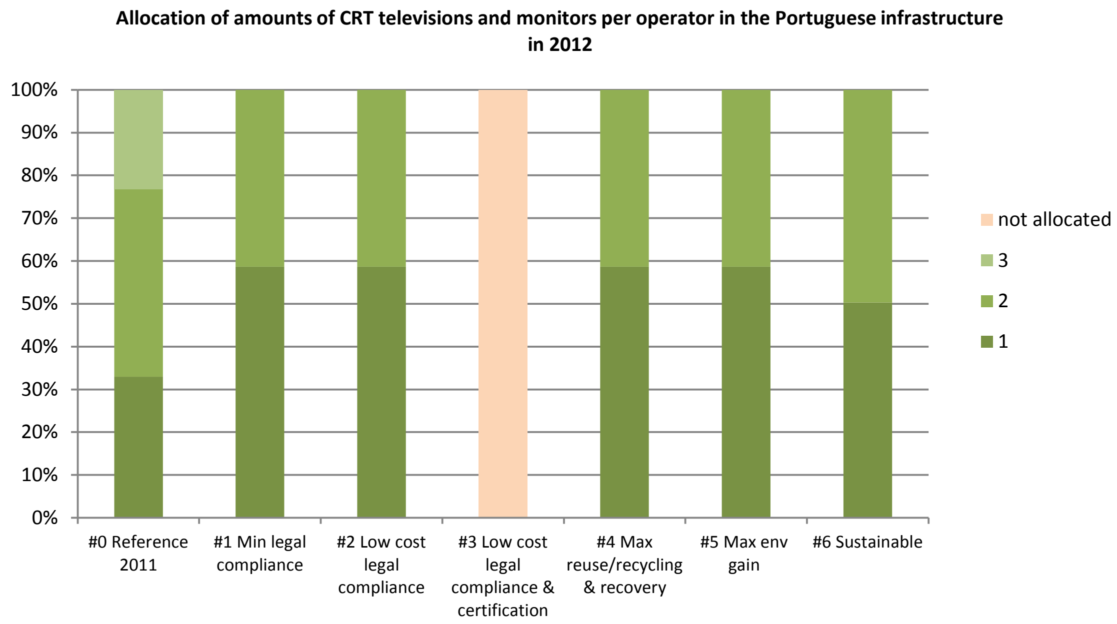
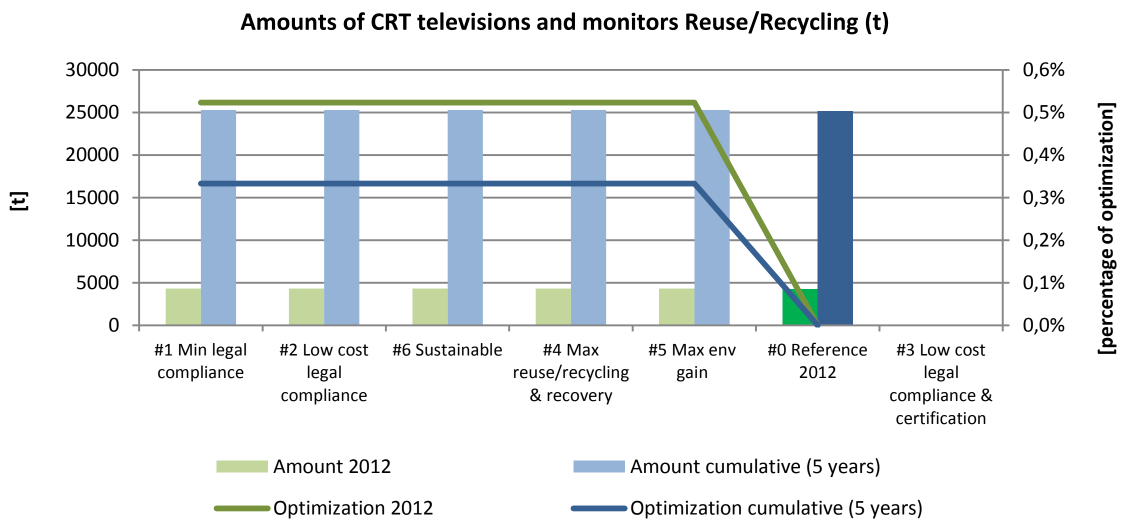


Figure 4.41 – Allocation of amounts of CRT televisions and monitors per operator in the Portuguese infrastructure in 2012 (calculated)

4.3.5.1 Technical performance

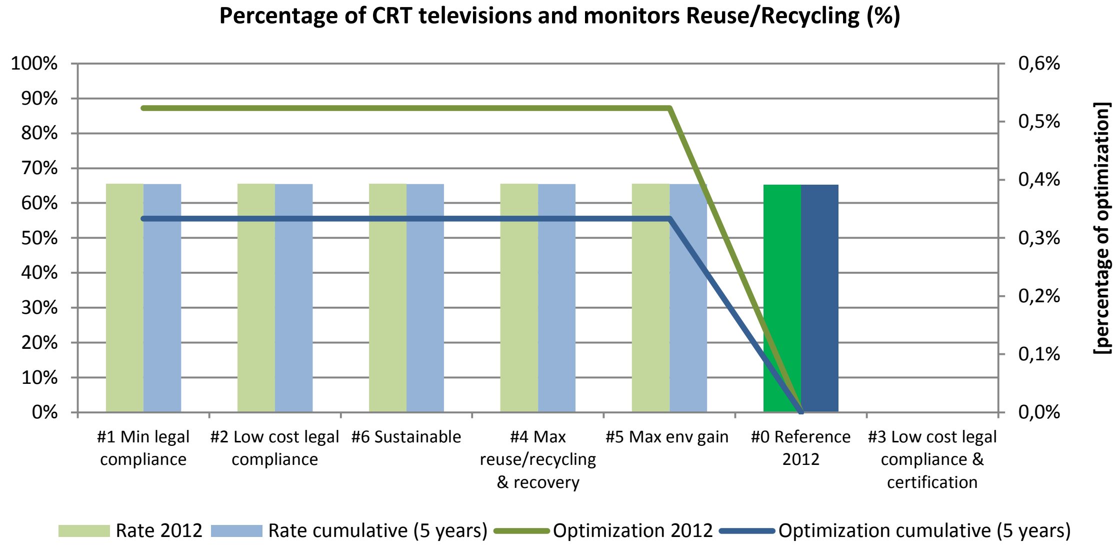
The technical performance of the treatment and recovery of CRT televisions and monitors in the Portuguese infrastructure was assessed in the different scenarios. Figure 4.42 and Figure 4.43 present the results regarding WEEE reuse/recycling.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.42 – Amounts of CRT televisions and monitors Reuse/Recycling in the Portuguese infrastructure

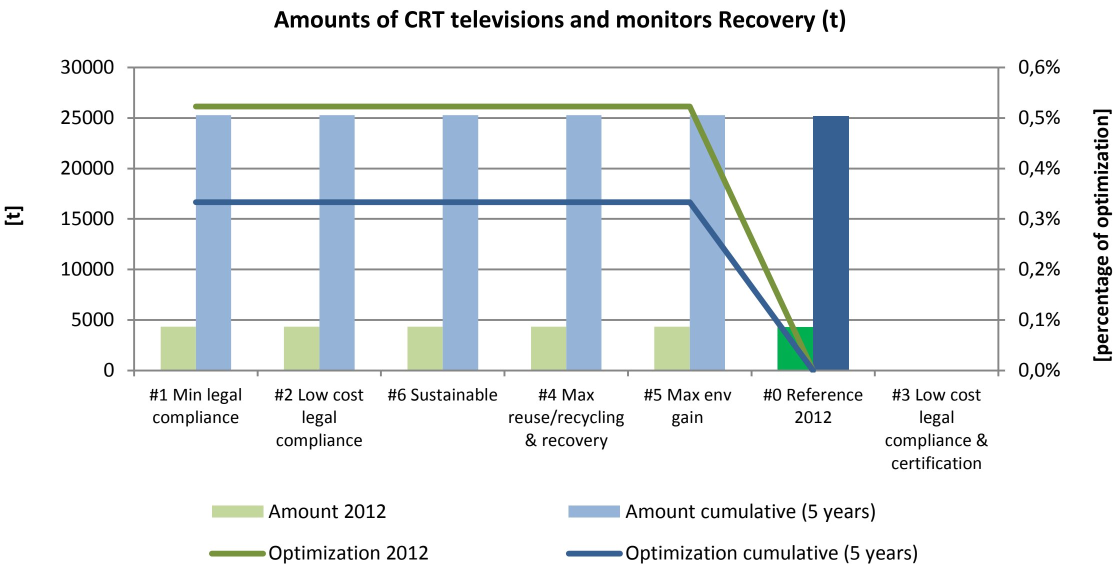
The results indicate that it is possible to improve from the current reference performance level, although only marginally, up to 0.5%. This is the consequence of the homogeneous performance of the individual operators in the Portuguese infrastructure.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.43 – Percentage of CRT televisions and monitors Reuse/Recycling in the Portuguese infrastructure

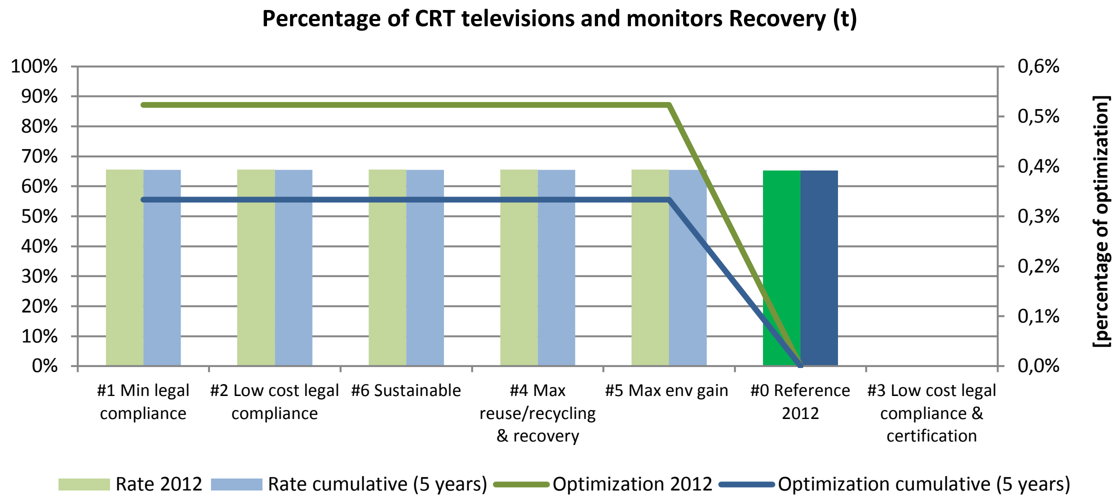
Figure 4.44 and Figure 4.45 present the results regarding WEEE recovery.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.44 – Amounts of CRT televisions and monitors Recovery in the Portuguese infrastructure

The current performance levels can only be improved marginally, which in this case is of significant consequence, since the operators are performing under the level required to fulfil the legal targets. Thus, significant improvements are required, most likely from changes in the technologies utilized by the operators, if they are to reach the 75% value of the legal target on recovery defined in the WEEE Directive.

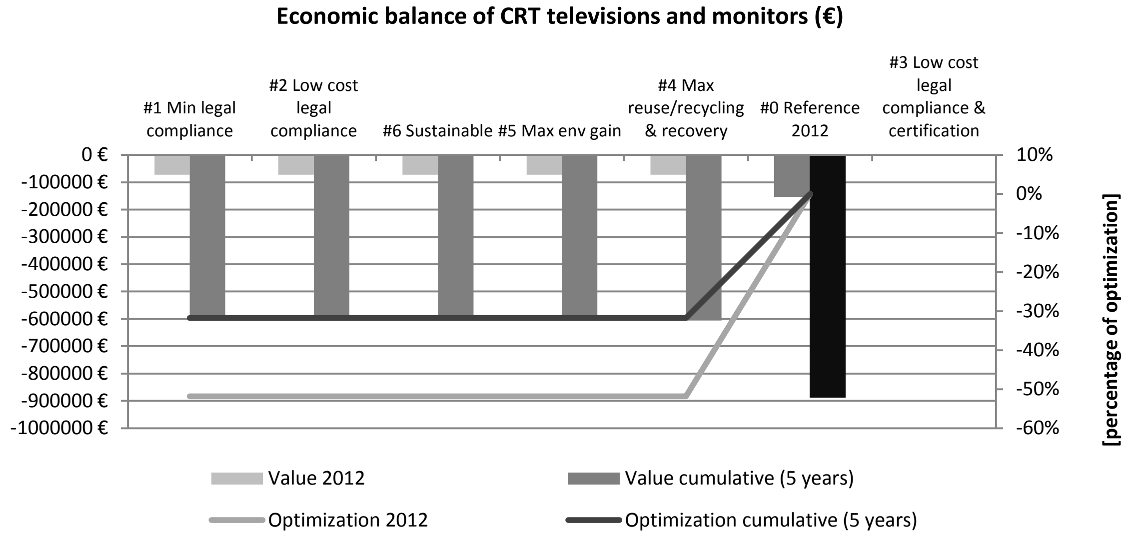


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.45 – Percentage of CRT televisions and monitors Recovery in the Portuguese infrastructure

4.3.5.2 Economic performance

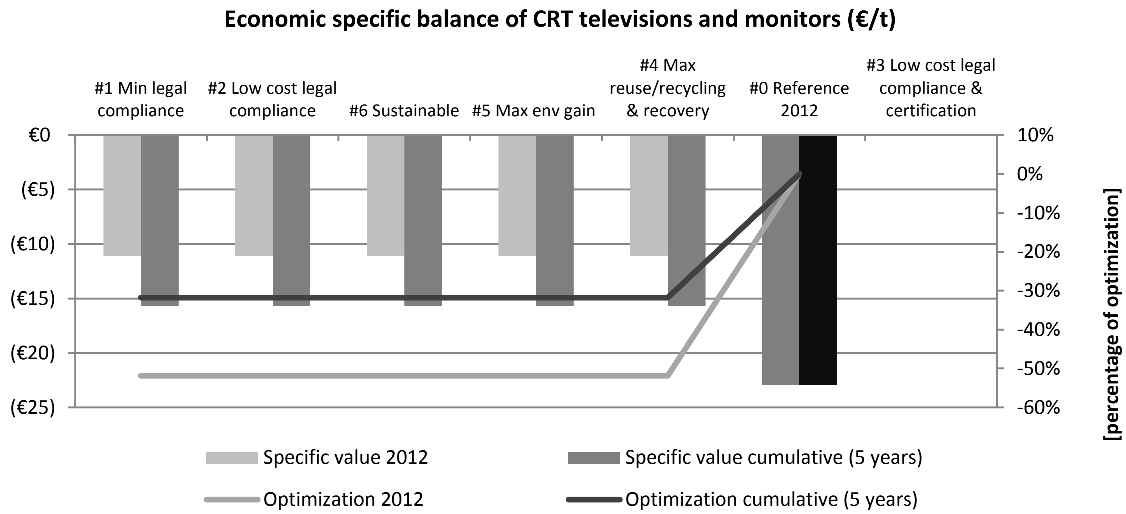
The treatment and recovery of CRT televisions and monitors presents a negative economic balance, considering the Portuguese infrastructure and the downstream processes. According with the results in Figure 4.46 and Figure 4.47, this economic burden may be reduced more than 30% over a 5 year period, and more than 50% if considering the year 2012 alone.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.46 – Economic balance of CRT televisions and monitors in the Portuguese infrastructure

These results are relevant considering the legal responsibility of PRO's to finance the treatment and recovery of WEEE. In theory, the financial assistance necessary for operators to process CRT televisions and monitors could be reduced and they would still fulfil the legal targets.

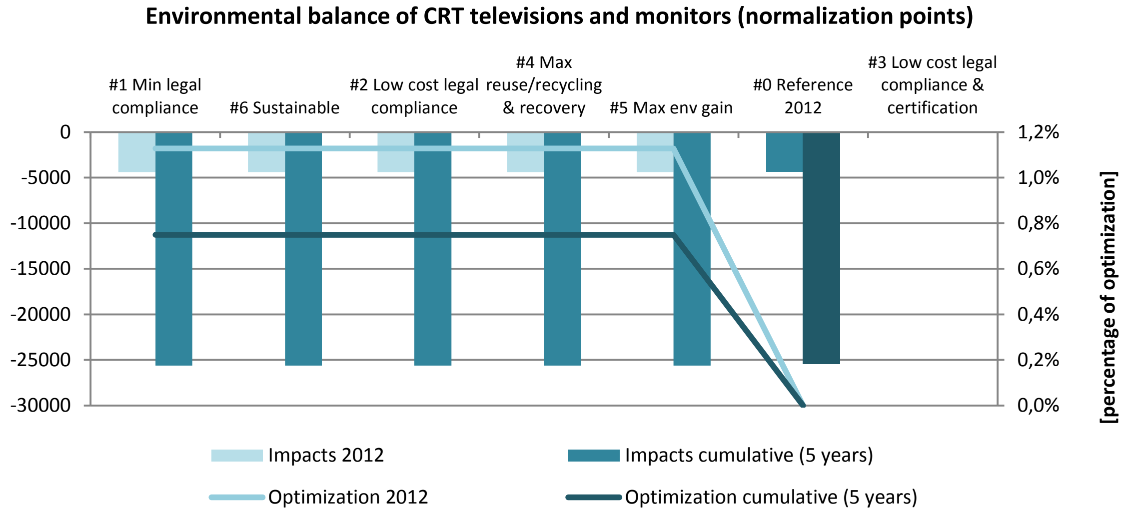


Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.47 – Economic specific balance of CRT televisions and monitors in the Portuguese infrastructure

4.3.5.3 Environmental performance

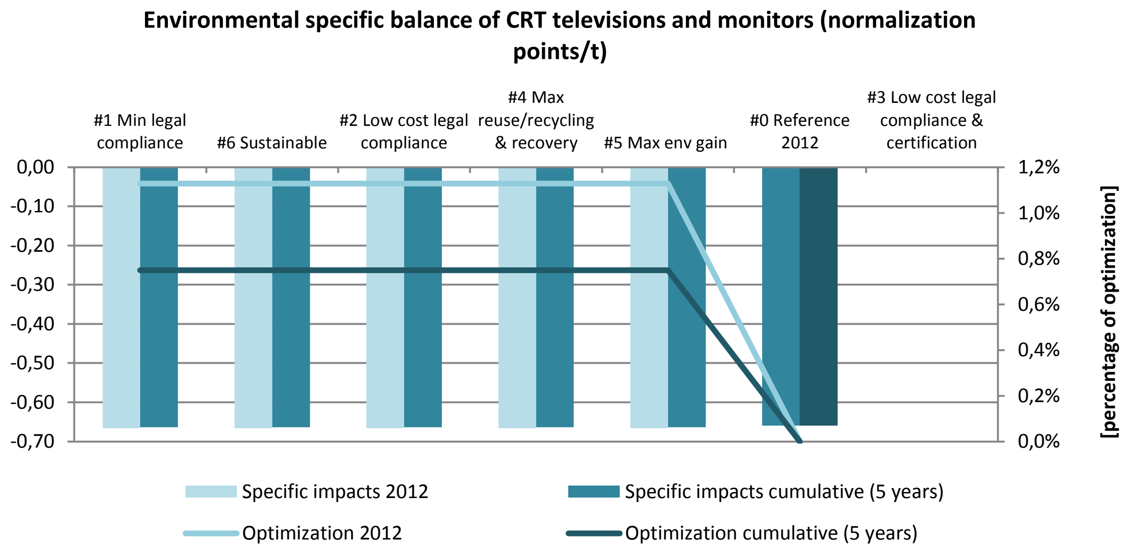
The treatment and recovery of CRT televisions and monitors presents an environmental gain. Figure 4.48 and Figure 4.49 show the respective absolute and specific environmental impacts.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.48 – Environmental balance of CRT televisions and monitors in the Portuguese infrastructure

The results indicate that the current environmental performance levels can be improved slightly, by approximately 1%. Overall, with the exception of scenario #3, all the other scenarios presented improvements on the reference performance considering the technical, economic and environmental aspects.



Note: Scenarios sorted from the highest to the lowest performance (reference scenario highlighted).

Figure 4.49 – Environmental specific balance of CRT televisions and monitors in the Portuguese infrastructure

4.4 Improving the total WEEE treatment and recovery performance

The processing of WEEE is done independently in each of the five treatment categories. This means that specific strategies can be taken individually for each category in order to improve its performance and pursue designated objectives set by the stakeholders, namely the PRO's and the government authorities.

The results of the previous section show that there are different alternatives to improve the individual performance of each category at the technical, economic and environmental levels. By adding the mostly improved performance of each category, at each level, the improved total performance of all categories together at each level is obtained.

In the perspective of the PRO's, the assessment of the improved total performance of WEEE treatment and recovery allows to identify the benchmark performance of the entire Portuguese infrastructure specifically in the technical, economic and environmental levels. This allows to identify the boundaries for improvement and to understand in what direction the objectives for improvement should be set.

In the following subsections, the improved total performance in the Portuguese infrastructure in the technical, economic and environmental levels is presented for the year 2012.

4.4.1 Improved total technical performance

The improved total technical performance was determined by selecting the individual results that improved mostly the technical performance in each of the treatment categories. The objective was to determine the maximum total technical performance, regardless of the impacts in the remaining aspects.

Table 4.11 presents the improved total technical performance of WEEE treatment and recovery in the Portuguese infrastructure and compares it with the reference total performance.

Table 4.11 – Improved total technical performance in 2012

	#0 Reference total performance	Improved total technical performance (1)	Variation
Reuse/Recycling (t)	**38856**	**40060**	**3.1%**
Recovery (t)	**39048**	**40167**	**2.9%**
Economic balance (€)	1650846	1835166	11.1%
Financial assistance (€)	-610662	-470914	-22.8%
Environmental balance (normalization points)	-43177	-44827	3.8%
Reuse/Recycling (%)	**79.3**	**81.7**	**3.1%**
Recovery (%)	**79.7**	**82.0**	**2.9%**
Economic balance (€/t)	33.7	37.4	11.1%
Financial assistance (€/t)	-12.5	-9.6	-22.8%
Environmental balance (normalization points/t)	-0.88	-0.91	3.8%

Notes: (1) Includes data of all the WEEE treatment categories, in each of them from the specific scenario that presented the greatest improvement of the technical performance (Large household appliances scenario #4; Cooling and freezing appliances scenario #1; Small domestic appliances scenario #5; Gas discharge lamps scenario #0 and CRT televisions and monitors scenario #1).

The results show that the improved total technical performance presents an increase of 3.1% in reuse/recycling and an increase of 2.9% in the recovery of the WEEE processed in the Portuguese infrastructure.

4.4.2 Improved total economic performance

The improved total economic performance was determined by selecting the individual results that improved mostly the economic performance for each of the treatment categories. The objective was to determine the maximum economic performance, regardless of the impacts in the remaining aspects.

Table 4.12 presents the improved total economic performance of WEEE treatment and recovery in the Portuguese infrastructure and compares it with the reference total performance.

Table 4.12 – Improved total economic performance in 2012

	#0 Reference total performance	Improved total economic performance (1)	Variation
Reuse/Recycling (t)	38856	37931	-2.4%
Recovery (t)	39048	38038	-2.6%
Economic balance (€)	**1650846**	**2283877**	**38.3%**
Financial assistance (€)	**-610662**	**-268885**	**-55.9%**
Environmental balance (normalization points)	-43177	-42852	-0.8%
Reuse/Recycling (%)	79.3	77.4	-2.4%
Recovery (%)	79.7	77.6	-2.6%
Economic balance (€/t)	**33.7**	**46.6**	**38.3%**
Financial assistance (€/t)	**-12.5**	**-5.5**	**-55.9%**
Environmental balance (normalization points/t)	-0.88	-0.87	-0.8%

Notes: (1) Includes data of all the WEEE treatment categories, in each of them from the specific scenario that presented the greatest improvement of the economic performance (Large household appliances scenario #2; Cooling and freezing appliances scenario #0; Small domestic appliances scenario #1; Gas discharge lamps scenario #6 and CRT televisions and monitors scenario #1).

The results show that the improved total economic performance presents an increase of 38.3% in the economic balance which translates in to a reduction of 55.9% in the financial assistance required to ensure the treatment and recovery of the WEEE processed in the Portuguese infrastructure.

4.4.3 Improved total environmental performance

The improved total environmental performance was determined by selecting the individual results that improved mostly the environmental performance for each of the treatment categories. The objective was to determine the improved total environmental performance, regardless of the impacts in the remaining aspects.

Table 4.13 presents the improved total environmental performance of WEEE treatment and recovery in the Portuguese infrastructure and compares it with the reference total performance.

Table 4.13 – Improved total environmental performance in 2012

	#0 Reference total performance	Improved total environmental performance (1)	Variation
Reuse/Recycling (t)	38856	38427	-1.1%
Recovery (t)	39048	38559	-1.3%
Economic balance (€)	1650846	2.016148	22.1%
Financial assistance (€)	-610662	-385781	-36.8%
Environmental balance (normalization points)	**-43177**	**-46675**	**8.1%**
Reuse/Recycling (%)	79.3	78.4	-1.1%
Recovery (%)	79.7	78.7	-1.3%
Economic balance (€/t)	33.7	41.1	22.1%
Financial assistance (€/t)	-12.5	-7.9	-36.8%
Environmental balance (normalization points/t)	**-0.88**	**-0.95**	**8.1%**

Notes: (1) Includes data of all the WEEE treatment categories, in each of them from the specific scenario that presented the greatest improvement of the environmental performance (Large household appliances scenario #5; Cooling and freezing appliances scenario #5; Small domestic appliances scenario #5; Gas discharge lamps scenario #6 and CRT televisions and monitors scenario #1).

The results show that the improved total environmental performance presents an increase of 8.1% in the environmental balance of the treatment and recovery of the WEEE processed in the Portuguese infrastructure.

5 Conclusions and Recommendations

5.1 Revisiting the research questions

The principle of Extended Producer Responsibility has been adopted by governments of European and other countries worldwide as the leading policy instrument to address the end-of-life management of products, in order to minimize the environmental impacts, increase the recovery of the material and energy content from waste and to minimize the cost of waste management and shift it from the taxpayer on to the producers and consumers of the products.

With the implementation of EPR to waste electrical and electronic equipment, a significant number of producer responsibility organizations were constituted and licensed by government authorities to develop WEEE management systems at national level, in order to fulfil legal objectives on collection, treatment and recovery. Within their responsibilities and competencies, the PRO's have signed contracts with operators that own and operate the technologies capable of processing the WEEE. The outputs from these operators are passed on to downstream operators for additional processing and ultimately for recovery or elimination.

Despite the systemic and technological developments, the achievement of the legal targets on the recovery of WEEE is still hampered by the lack of end-of-life technologies and the misuse of those currently available. Because the know-how on the end-of-life technologies is held by the operators, being an important part of business, it has remained unavailable to the PRO's, the policy makers and the producers of EEE. Ultimately, this became an important barrier for the efficient and effective management of the WEEE.

The fundamental objective of the present thesis consisted on developing a model of the end-of-life processing and recovery infrastructure for WEEE and use it to improve the performance of the WEEE treatment and recovery considering the technical, economic and environmental aspects. Based on the WEEE take back systems and the leading role of PRO's in the management of WEEE, the objectives entailed the following research questions:

- How can technical/economic models be developed in order to successfully characterize the key treatment and recovery processes for WEEE?
- How can the PRO's apply these models to develop the efficient use of technologies and improve the treatment and recovery of WEEE?
- How can this information be used to promote ecodesign?

5.2 Main findings

The research work provided important contributions to answer the research questions as follows.

1. **How can technical/economic models be developed in order to successfully characterize the key treatment and recovery processes?**

Results in chapter 2 and chapter 3 presented important contributions to answer the first research question. The lack of knowledge on the treatment and recovery processes has been identified in the pertinent literature as a decisive barrier to the efficient and effective recovery of waste electrical and electronic equipment. Although PRO's are legally responsible to achieve specific legal targets on reuse/recycling and recovery of WEEE, in the context of EPR based WEEE management systems they do not own the operational capability and the respective know-how on the end-of-life processing technologies. In fact, the WEEE processing operators from the public and private sectors with which the PRO's sign service contracts are the owners of the end-of-life technologies and the holders of the specific knowledge.

Because the end-of-life processing of the WEEE is done by the referred operators as part of their business activities, the knowledge on the end-of-life technologies, the equipment, the trained personnel and the operational practices are all factors of market competitiveness and naturally are not disclosed publically nor even to the PRO's. The research work developed a methodology for WEEE end-of-life processing tests in order to make available data on the end-of-life technologies. The extensive campaign of WEEE processing tests implemented in the research work described in chapter 2 involved the Portuguese infrastructure constituted a case study of some of the best available technologies currently used to process WEEE of all its different categories.

The research work also showed that it is necessary to overcome the default unwillingness of the operators to be part of the WEEE processing tests. The initial position of most operators was sceptic and did not recognize the advantages of performing the tests on their facilities. However, when the tests were completed and the results were presented to them, most of them acknowledged the positive impact on their activity, for example by helping to identify problems with the practices and the processes that they had been using to process the WEEE. Probably one of the most important learnings from the campaign of WEEE processing tests was that it could not have been done without the direct involvement of the PRO's in the preparation and the execution of the tests. These organizations are the main clients of the WEEE processing operators and consequently have a strong capability to make demands as it was the case in the research work.

Another important learning was that the attitude of PRO's towards developing the knowledge on the end-of-life technologies is associated with the expectations that come from the respective associate producers; in Portugal many of them are importers of EEE and present an attitude of *pay to forget*, i.e. basically pay the ecovalue to comply with the legal responsibilities and do not worry about the management of WEEE. This would normally be expected as producers are more focused on increasing sales. However, in the present times there are significant economic strains on the management of WEEE with the decreasing revenue from ecovalue as a result of reduction of sales volumes of new products and from the increasing legal objectives on the collection and recovery of WEEE defined in the WEEE Recast. In this context,

there is a need to increase the efficiency and the effectiveness of the end-of-life processing of WEEE and so more attention is given by PRO's to the operational management of WEEE, in particular the treatment and recovery.

The results in chapter 3 show how it is possible to develop technical, economic and environmental models which make the knowledge on the operations for the entire end-of-life processing chain for WEEE available to PRO's and other stakeholders. The results also showed that the models can be used to assess the end-of-life performance of operations and technologies, considering the technical economic and environmental aspects.

The end-of-life processing chain for WEEE is composed of several processing stages which may occur in different countries, and the research work provided a full characterization of the treatment and recovery of WEEE for the Portuguese infrastructure and the downstream operations. This helped demonstrate that the different operations entail specific inefficiencies from the technical, economic and environmental perspectives with consequences on the total performance of the WEEE treatment and recovery. In general, such inefficiencies are not quantified and made visible to PRO's mostly because these organizations only interact with the operators responsible for the initial operations of end-of-life processing of the WEEE. Consequently, because of the legal responsibilities of PRO's to finance and ensure the recovery of WEEE, they end up filling in for the inefficiencies of the entire end-of-life processing chain.

The research results regarding the assessment of the performance of WEEE treatment and recovery for the different types of WEEE brought insight on the inefficiencies along the Portuguese infrastructure and downstream operations. The results showed that there are some limitations to the present and future technical capability to achieve the legal targets on reuse/recycling and recovery of WEEE when considering the performance of all the stages of the processing chain, in particular for cooling and freezing appliances and for CRT televisions and monitors. The limitations on the recovery of WEEE are associated with the capability of the processing technologies to separate the materials but also with the capability of the recovery technologies to make use of the materials, and from the markets to buy those materials.

The results also showed that the treatment and recovery of the metal content dominated WEEE such as large household appliances and cooling and freezing appliances presents an overall economic positive value while for the remaining WEEE dominated by plastic and glass content, the economic balance is generally negative. As PRO's are legally required to provide the financial assistance necessary to ensure the treatment and recovery of WEEE, the results meant that in theory they would only have to support the cost for the treatment and recovery of small domestic appliances, gas discharge lamps and CRT televisions and monitors. In practice however, many PRO's provide financial assistance for all types of WEEE to attend the demands of the WEEE processing operators. The PRO's end up supporting the economic inefficiencies of the entire WEEE processing chain, including unfair profit margins and price speculation played by downstream operators.

A similar situation happens with the environmental inefficiencies of processing. The environmental models developed demonstrated that the WEEE treatment and recovery has positive and negative impacts although, overall, it represents an environmental gain.

Under the current framework of EPR based WEEE management systems, it has not been the core activity of the PRO's to perform the operations of WEEE processing themselves, instead they have outsourced it. However, in the future it may be important for these organizations to develop competencies and intervene more directly in the end-of-life processing in order to improve the transparency and control over the operations and increase the efficiency of the WEEE treatment and recovery.

The research presented in chapter 2 and chapter 3 demonstrated that it is possible to build models that developed the knowledge on the technical, economic and environmental aspects of the end-of-life processing technologies for WEEE and make it available to the stakeholders.

The global model was developed based on data from field work and complemented with data from bibliographical sources and from technology providers, which present different levels of quality and credibility. Data from the experimental tests was of very high quality because of its nature and the procedures enforced during the execution. Bibliographical data was also of high quality, although it proved outdated in particular regarding some of the most recent technologies. Additional data was collected from technology providers, which was of questionable quality in some cases, mostly regarding information that was used for commercial purposes. Its use in the research was kept at a minimum necessary. Finally, market data was used from sources commonly used by the operators in the WEEE business, which are trustful despite the respective data being volatile.

Because the global model was developed using an Excel based tool it is very easy to disseminate it. The tool allows the user to change the input data of the processes that are already modelled and to create new ones. A database was also developed and built along the research work to incorporate the technical, economic and environmental data of all the processes used in the global model. This allows stakeholders to build up from the global model or to develop their own models from start, to use the already existing database and to create new processes.

In order for the global model developed in the research work to continue to be useful in the future it requires updating with the latest data on the existing technologies and upgrading with the upcoming technologies. To ensure this, the characterization of the end of life processing technologies for WEEE should be done on a regular basis. The WEEE processing tests are a method to obtain effective performance data from technologies. Other methods can be used, based on bibliographical data.

2. **How can the PRO's apply these models to develop the efficient use of technologies to improve the treatment and recovery of WEEE?**

Chapter 3 presented the assessment of the current performance of WEEE treatment and recovery in the Portuguese infrastructure. This established the reference performance level which was used to determine if the WEEE treatment and recovery could be improved by developing the efficient use of the end-of-life technologies.

In the context of the legal responsibilities and their competencies, the PRO's ensure the collection of WEEE and determine the allocation of the respective amounts to the WEEE processing operators; by doing so they determine the use of the end-of-life technologies. A set of rules was established to determine the allocation of the amounts of WEEE by the operators in the Portuguese infrastructure with the objective of improving the global performance of WEEE treatment and recovery considering the technical, economic and environmental aspects. The rules were incorporated in distinct scenarios that prioritized the different variables, namely the reuse/recycling and recovery targets, the economic and the environmental balances.

Chapter 4 presented the results of efficient use of end-of-life technologies in the Portuguese infrastructure, over a 5 year period. The results showed that the treatment and recovery performance could be improved for WEEE of each category. In particular, they indicated that the technical and environmental performance could be improved most significantly for large household appliances (5.8% on recovery, 31.3% on economic balance and 11.8% on environmental balance) and for small domestic appliances (1.9% on recovery, 12.2% on economic balance and 10.6% on environmental balance), while for cooling and freezing appliances, gas discharge lamps and CRT televisions and monitors it was possible to improve but less significantly (between 0.1% and 0.5% on recovery, no significant changes to the economic balance and 0.2% to 1.1% on environmental balance). It was also possible to significantly cut the financial assistance provided by PRO's to ensure the treatment and recovery of some WEEE categories, namely small domestic appliances (-85.1%), gas discharge lamps (-45.1%) and CRT televisions and monitors (-51.8%). For large household appliances and cooling and freezing appliances results show that no financial assistance should be provided.

The research showed how much it is possible to improve the total performance of WEEE treatment and recovery, considering the five WEEE treatment categories altogether. For the case study of the Portuguese infrastructure and the downstream operations, the results in chapter 4 demonstrated that the total performance of WEEE treatment and recovery can be improved in all three dimensions, technical, economic and environmental by developing a more efficient use of the available end-of-life technologies.

The results showed that for the year 2012 in Portugal it was possible to increase the amounts of WEEE recovery by more than 1000 tons and increase up to 3.1% and 2.9% respectively the reuse/recycling and recovery rates. Regarding the economic balance, it was possible to achieve a net positive value of more than 2.2 million euros representing an increase of 38.3% compared to the current performance level, and reduce the costs of PRO's by approximately 55.9%. Finally,

despite the current environmental balance representing a total gain, the results showed that it can be improved by as much as 8.1% by improving the WEEE treatment and recovery.

These results are significant and demonstrate that there is still considerable margin for improvement of the WEEE treatment and recovery performance in the context of the EPR based WEEE management systems. It was also made evident that there are different options to improve the WEEE treatment and recovery, considering the trade-offs between the different technical, economic and environmental variables. Thus, it is important that the PRO's clearly define the objectives regarding the performance of WEEE treatment and recovery and the direction in which they want to improve it.

Very shortly, by 2014 approximately, there will be a shortage in the capability to process cooling and freezing appliances and small domestic appliances in the Portuguese infrastructure. Having an infrastructure that can provide the capacity to process WEEE in all the treatment categories is essential and not even the improvement of the use of end-of-life technologies can overcome this lack.

In parallel, the research also showed that some legal requirements cannot be achieved with the current technologies installed in the Portuguese infrastructure, including the downstream operations. This was evident for the recovery of cooling and freezing appliances and CRT televisions and monitors. In both cases, despite some of the best available technologies being used, it is not possible to comply with legal targets because of the unavailability of markets for some of the secondary materials that are obtained. The lead containing glass from CRT televisions and monitors and the polyurethane insulating foam from cooling and freezing appliances are two examples of material fractions which have low demand and are often eliminated instead of being recovered.

Both situations described previously show that the enhancement of WEEE treatment and recovery is not exclusively dependent on the performance of the end-of-life technologies, but also from the development of markets and applications for the secondary materials. As the research showed, the efficient use of end-of-life technologies has a limit on how far it can enhance WEEE treatment and recovery and so PRO's and other stakeholders have to address the development of new end-of-life technologies and the promotion of new markets for secondary materials.

The global model developed in the research work can be easily accessible to PRO's and they can use it to develop the efficient use of the existing end-of-life technologies. Regarding the increasing need for PRO's to foster the development of new technologies, it is important to upgrade the global model with data from new and upcoming processing technologies as they are being developed. PRO's as the main stakeholders in WEEE management have to work closer with technology providers and have preliminary characterizations of the developing technologies in order to assess what kind of impact they can have in the performance of WEEE treatment and recovery. The modelling tool allows the creation of new processes and the quick

development of models of new technologies, which can be used to calculate the potential for improvement.

3. **How can this information be used to promote ecodesign?**

The product designers and engineers are the stakeholders that can put into practice product design changes in order to improve the treatment and recovery of the WEEE. From the perspective of the end-of-life management, PRO's have an important responsibility in promoting ecodesign in particular to facilitate reuse, dismantling and recovery of WEEE, its components and materials. In this context, two aspects have to be considered: the ability and the motivation of the product manufacturers. Although this topic was not the focus of the present research, according with the research results it is possible to state that the PRO's should be in a position to attend both aspects.

Regarding the ability aspect, improving the product recovery is hindered by the lack of information on the return flow. The results of the research work give the PRO's specific and detailed knowledge on the end-of-life technologies and the performance of WEEE treatment and recovery. Additionally, the models of the operations and the global model can be used by product designers and engineers to determine the expected technical, economic and environmental performance of the treatment and recovery of any new product they develop, in particular considering the material composition and the mass of the product.

Regarding the motivation for ecodesign, manufacturers are certain to introduce changes to a product if that provides it with a competitive advantage. Based on the models developed in the research work, the PRO's and the manufacturers are able to determine the potential reuse/recycling and recovery rates, the economic and environmental balances for the product. Ultimately this can provide the basis for PRO's to develop incentives for products that present improved treatment and recovery performance. The most obvious would be to have distinct ecovalues for products in the same category where the best performing products would pay less, according with the benefits of their improved end-of-life performance. Many other types of incentives can be drawn from the comparative assessment of the treatment and recovery performance for individual products.

5.3 Future research

The research work developed the knowledge on the processing of WEEE and quantified the potential for improvement of the treatment and recovery performance, considering the current technologies and their technical, economic and environmental aspects. It would be very useful to determine the potential performance of the upcoming end-of-life technologies that may be in the stage of research and development (e.g. pilot-scale installations to recover rare earth metals, technologies to treat and recover photovoltaic panels added to the scope of the WEEE Recast) and calculate their potential impact on the future WEEE treatment and recovery

performance. The continuous update of the database with new processes and the development of models for new technologies is essential to maintain its usefulness to the stakeholders, namely the PRO's.

Another interesting development would be to have the use of the end-of-life technologies consider the logistics from the WEEE collection points to the first tier processing facilities. The logistics of WEEE collection has been the focus of extended research and the interconnection of it with the results of treatment and recovery could benefit the enhancement of the total performance of WEEE management.

Focusing on the responsibilities of PRO's to promote ecodesign, it may prove interesting to validate the model in order to assess the performance of individual electrical and electronic equipment. WEEE processing tests can be implemented to process batch amounts of single type products to compare it with the technical, economic and environmental results provided by the models. In case results are coincident, the models are proven as worthy to draw specific analysis of individual product performance on treatment and recovery and could then be used to develop different incentives for ecodesign.

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Annexes/Appendixes

Annex I. Scope of the WEEE legal framework

Table A.I.1 – Scope of the WEEE legal framework

Categories	Equipment
1. Large household appliances	Large cooling appliances Refrigerators Freezers Other large appliances used for refrigeration, conservation and storage of food Washing machines Clothes dryers Dish washing machines Cooking Electric stoves Electric hot plates Microwaves Other large appliances used for cooking and other processing of food Electric heating appliances Electric radiators Other large appliances for heating rooms, beds, seating furniture Electric fans Air conditioner appliances Other fanning, exhaust ventilation and conditioning equipment
2. Small household appliances	Vacuum cleaners Carpet sweepers Other appliances for cleaning Appliances used for sewing, knitting, weaving and other processing for textiles Irons and other appliances for ironing, mangling and other care of clothing Toasters Fryers Grinders, coffee machines and equipment for opening or sealing containers or packages Electric knives Appliances for hair-cutting, hair drying, tooth brushing, shaving, massage and other body care appliances Clocks, watches and equipment for the purpose of measuring, indicating or registering time Scales
3. IT and telecommunication equipment	Centralized data processing: Mainframes Minicomputers Printer units Personal computing: Personal computers (CPU, mouse, screen and keyboard included) Laptop computers (CPU, mouse, screen and keyboard included) Notebook computers

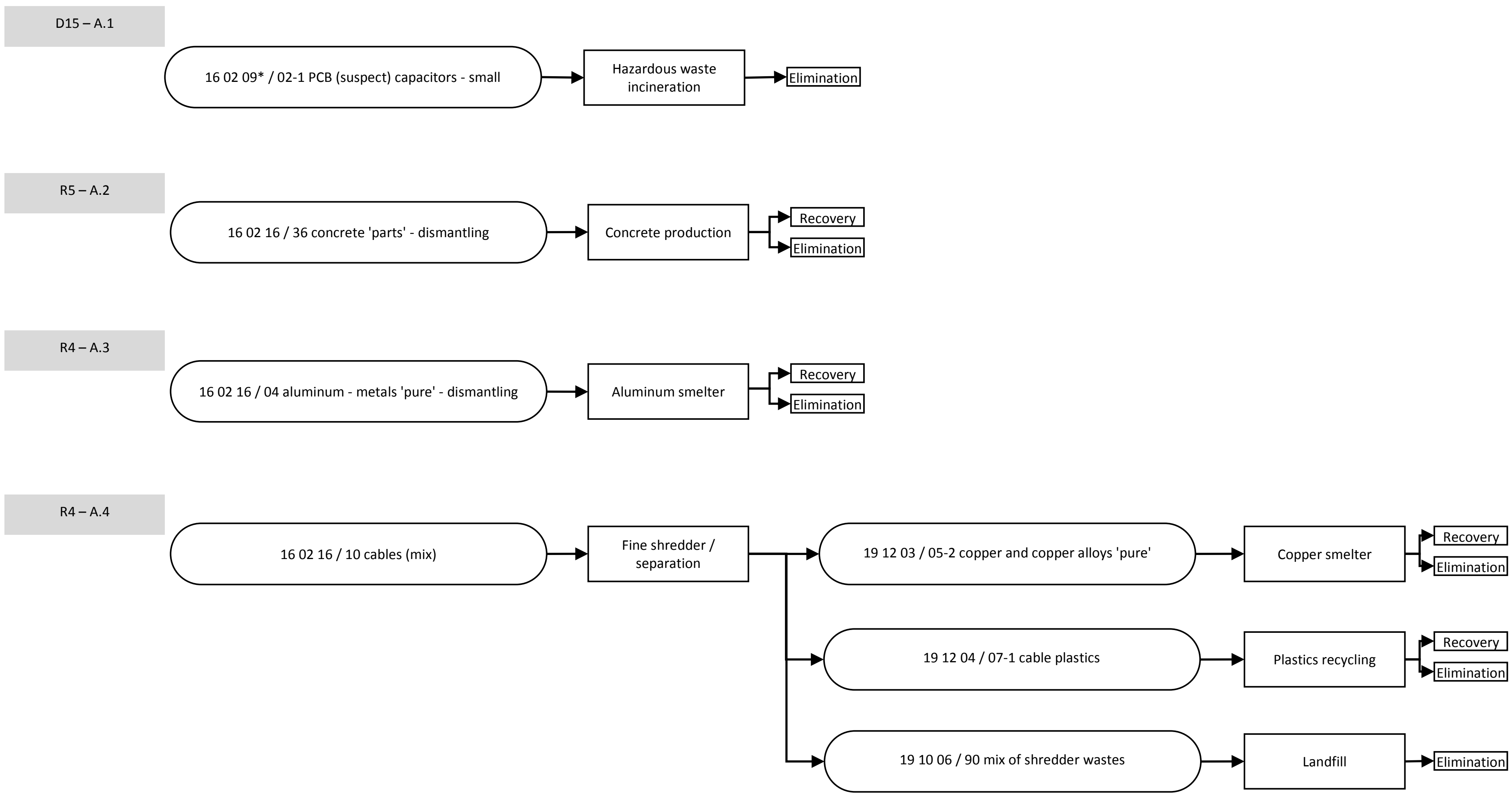
Categories	Equipment
	Notepad computers Printers Copying equipment Electrical and electronic typewriters Pocket and desk calculators and other products and equipment for the collection, storage, processing, presentation or communication of information by electronic means User terminals and systems Facsimile Telex Telephones Pay telephones Cordless telephones Cellular telephones Answering systems and other products or equipment of transmitting sound, images or other information by telecommunications
4. Consumer equipment (*) and photovoltaic panels	Radio sets Television sets Video cameras Video recorders Hi-fi recorders Audio amplifiers Musical instruments And other products or equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image than by telecommunications Photovoltaic panels (*)
5. Lighting equipment	Luminaries for fluorescent lamps with the exception of luminaries in households Straight fluorescent lamps Compact fluorescent lamps High intensity discharge lamps, including pressure sodium lamps and metal halide lamps Low pressure sodium lamps Other lighting or equipment for the purpose of spreading or controlling light with the exception of filament bulbs
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)	Drills Saws Sewing machines Equipment for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, making holes, punching, folding, bending or similar processing of wood, metal and other materials Tools for riveting, nailing or screwing or removing rivets, nails, screws or similar uses Tools for welding, soldering or similar use Equipment for spraying, spreading, dispersing or other treatment of liquid or gaseous substances by other means Tools for mowing or other gardening activities
7. Toys, leisure and sports equipment	Electric trains or car racing sets Hand-held video game consoles

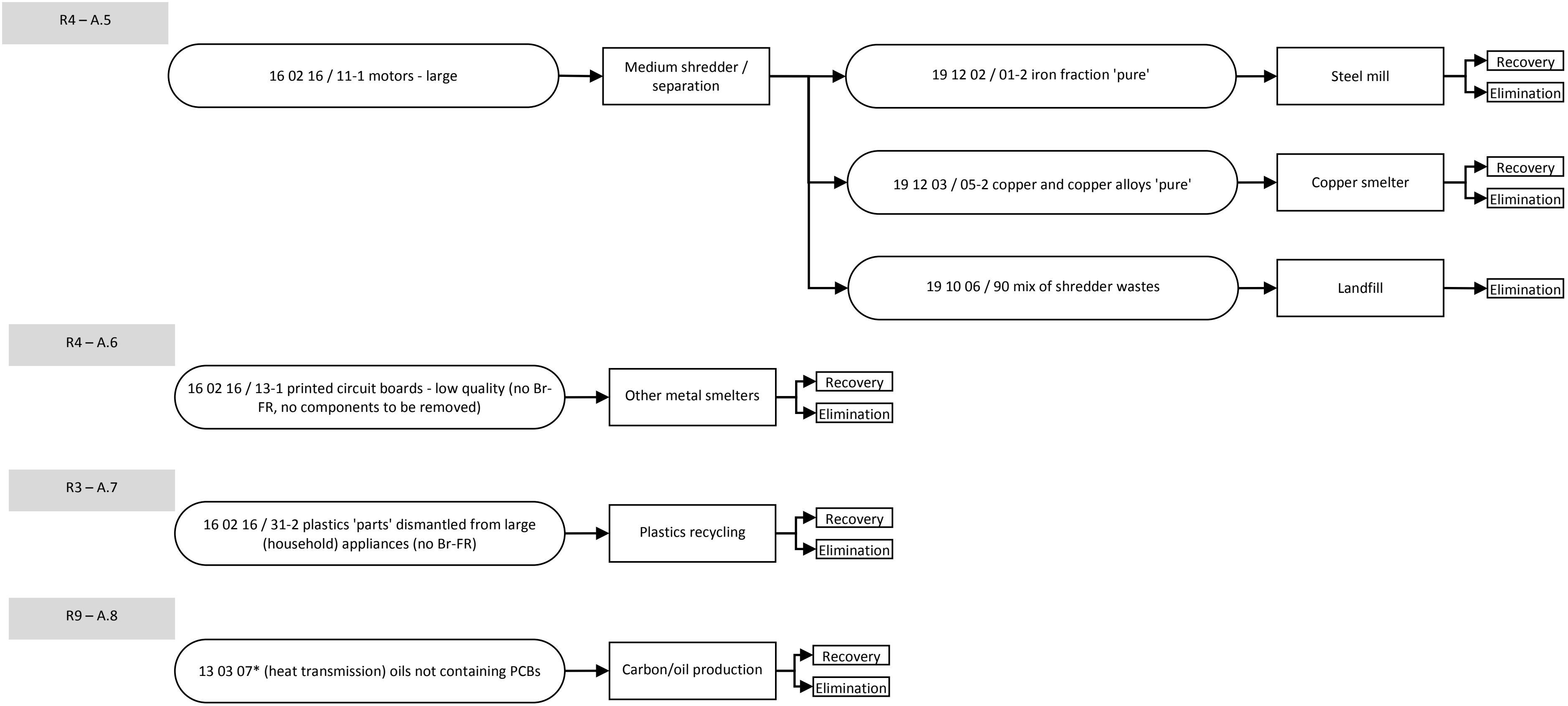
Categories	Equipment
	Video games Computers for biking, diving, running, rowing, etc. Sports equipment with electric or electronic components Coin slot machines
8. Medical devices (with the exception of all implanted and infected products)	Radiotherapy equipment Cardiology Dialysis Pulmonary ventilators Nuclear medicine Laboratory equipment for *in-vitro* diagnosis Analysers Freezers Fertilization tests Other appliances for detecting, preventing, monitoring, treating, alleviating illness, injury or disability
9. Monitoring and control instruments	Smoke detector Heating regulators Thermostats Measuring, weighing or adjusting appliances for household or as laboratory equipment Other monitoring and control instruments used in industrial installations (e.g. in control panels)
10. Automatic dispensers	Automatic dispensers for hot drinks Automatic dispensers for hot or cold bottles or cans Automatic dispensers for solid products Automatic dispensers for money All appliances which deliver automatically all kind of products

Notes: (*) Additionally included in the WEEE Recast

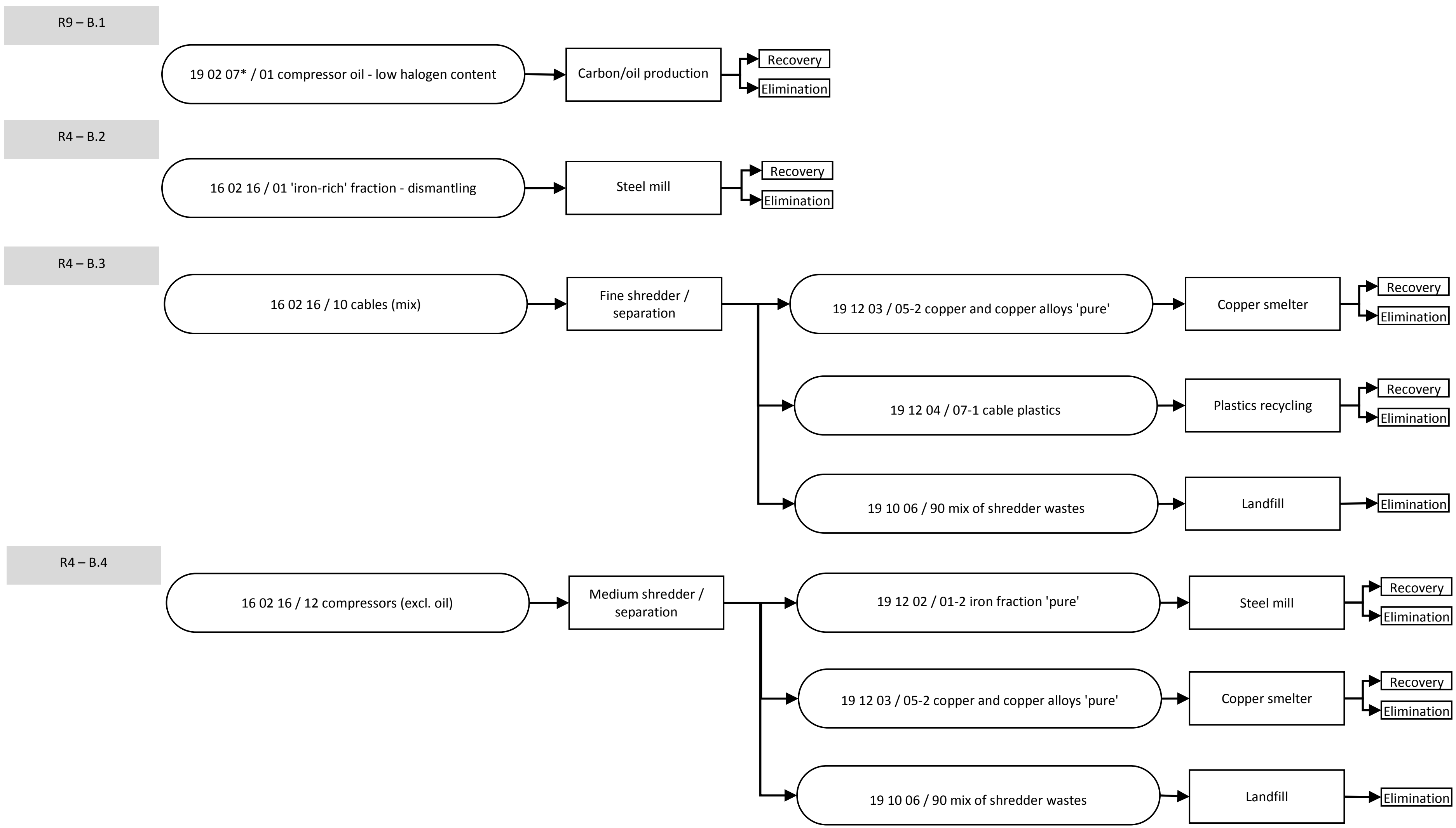
Annex II. Diagrams of the WEEE processing chains

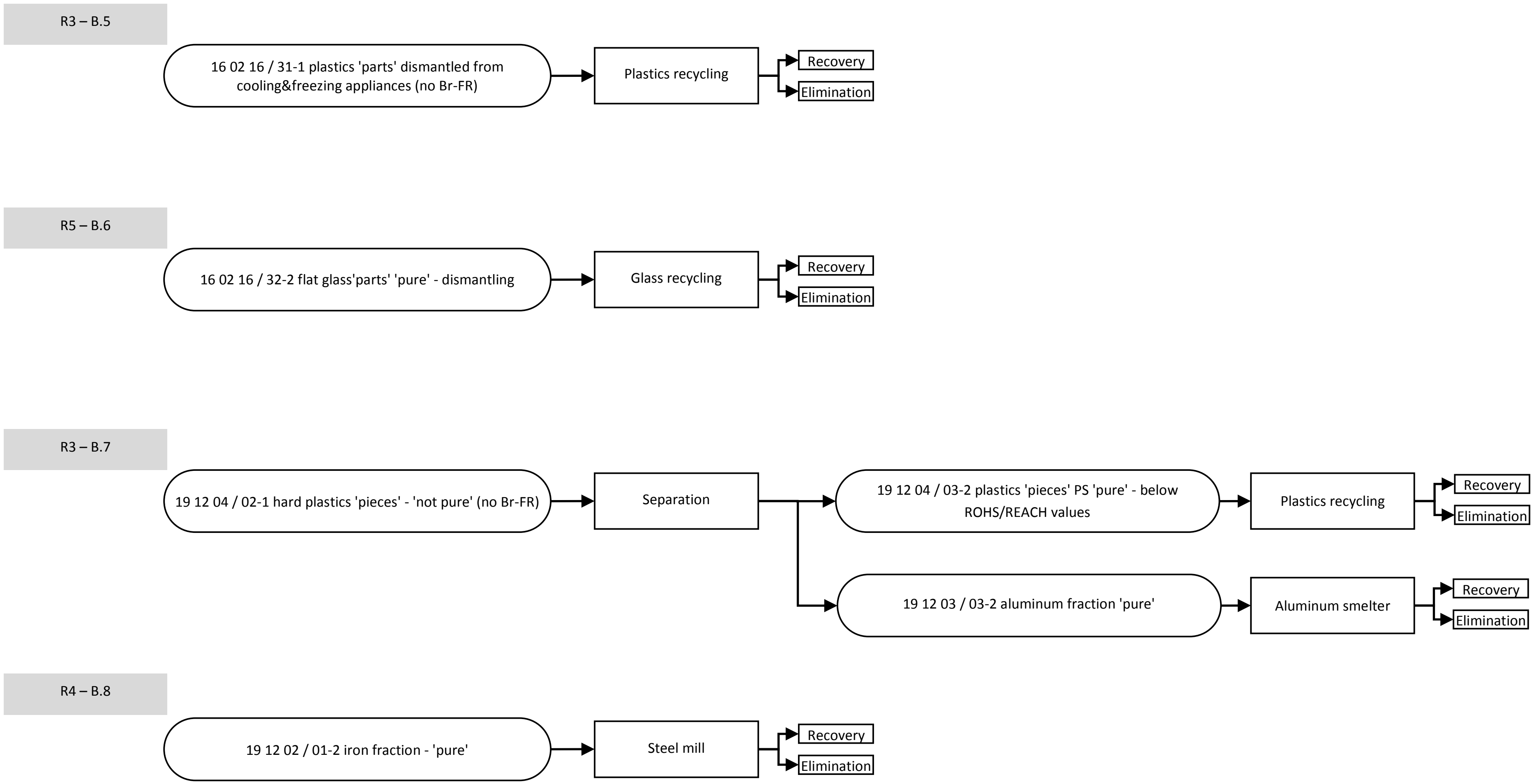
A. Large household appliances


D15 – A.1
16 02 09* / 02-1 PCB (suspect) capacitors - small
Hazardous waste incineration
Elimination
R5 – A.2
16 02 16 / 36 concrete 'parts' - dismantling
Concrete production
Recovery
Elimination
R4 – A.3
16 02 16 / 04 aluminum - metals 'pure' - dismantling
Aluminum smelter
Recovery
Elimination
R4 – A.4
16 02 16 / 10 cables (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 04 / 07-1 cable plastics
Plastics recycling
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination


R4 – A.5
16 02 16 / 11-1 motors - large
Medium shredder / separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination
R4 – A.6
16 02 16 / 13-1 printed circuit boards - low quality (no Br-FR, no components to be removed)
Other metal smelters
Recovery
Elimination
R3 – A.7
16 02 16 / 31-2 plastics 'parts' dismantled from large (household) appliances (no Br-FR)
Plastics recycling
Recovery
Elimination
R9 – A.8
13 03 07* (heat transmission) oils not containing PCBs
Carbon/oil production
Recovery
Elimination

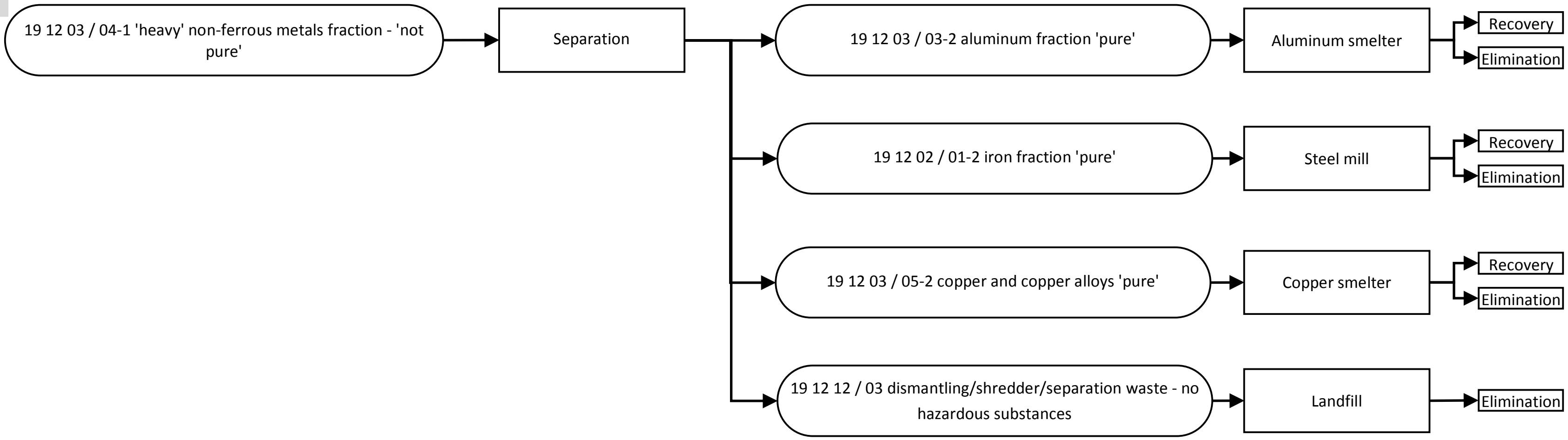
B. Cooling and freezing appliances


R9 – B.1
19 02 07* / 01 compressor oil - low halogen content
Carbon/oil production
Recovery
Elimination
R4 – B.2
16 02 16 / 01 'iron-rich' fraction - dismantling
Steel mill
Recovery
Elimination
R4 – B.3
16 02 16 / 10 cables (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 04 / 07-1 cable plastics
Plastics recycling
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination
R4 – B.4
16 02 16 / 12 compressors (excl. oil)
Medium shredder / separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination



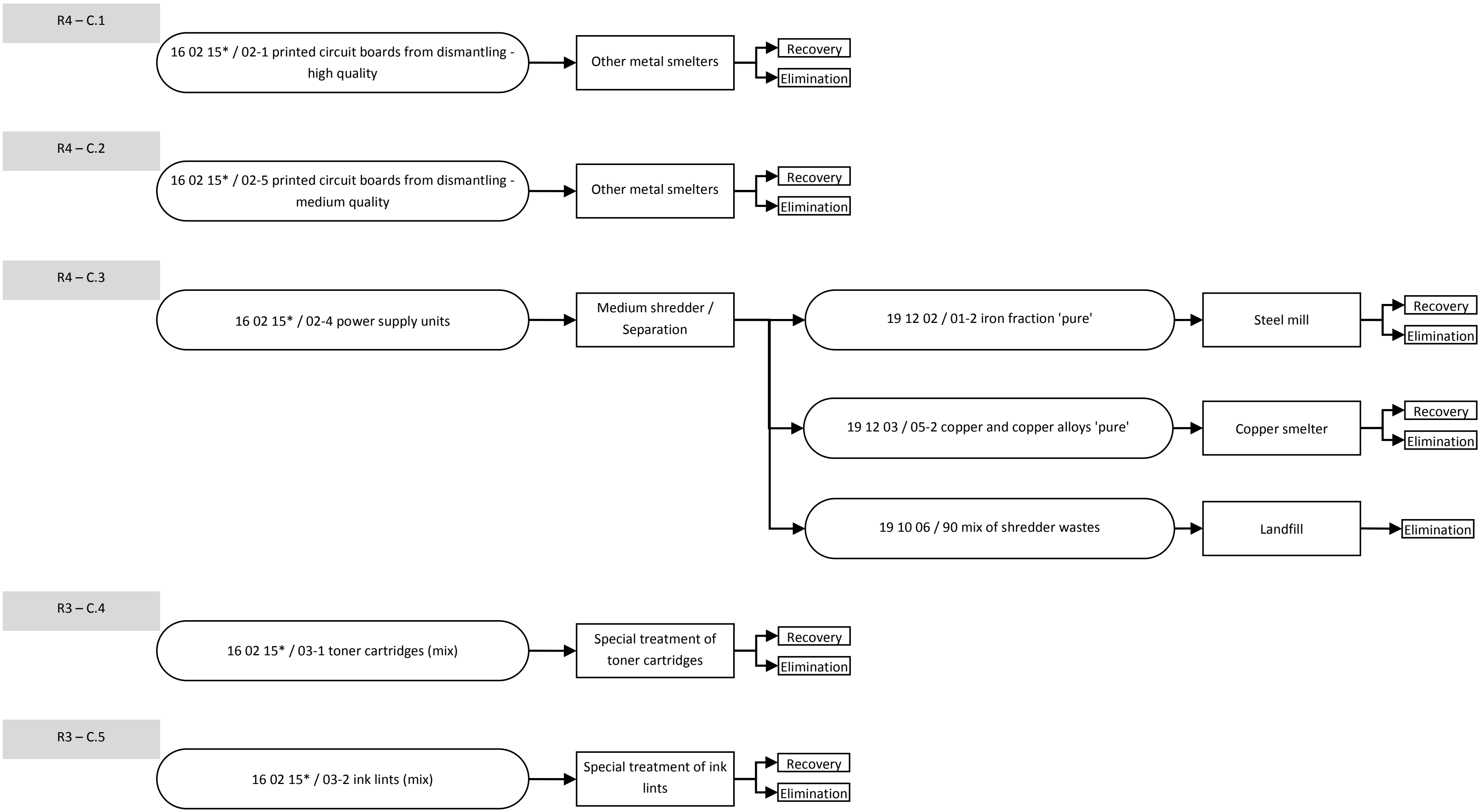
R3 – B.5
16 02 16 / 31-1 plastics 'parts' dismantled from cooling&freezing appliances (no Br-FR)
Plastics recycling
Recovery
Elimination
R5 – B.6
16 02 16 / 32-2 flat glass'parts' 'pure' - dismantling
Glass recycling
Recovery
Elimination
R3 – B.7
19 12 04 / 02-1 hard plastics 'pieces' - 'not pure' (no Br-FR)
Separation
19 12 04 / 03-2 plastics 'pieces' PS 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination
19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination
R4 – B.8
19 12 02 / 01-2 iron fraction - 'pure'
Steel mill
Recovery
Elimination

R4 – B.9

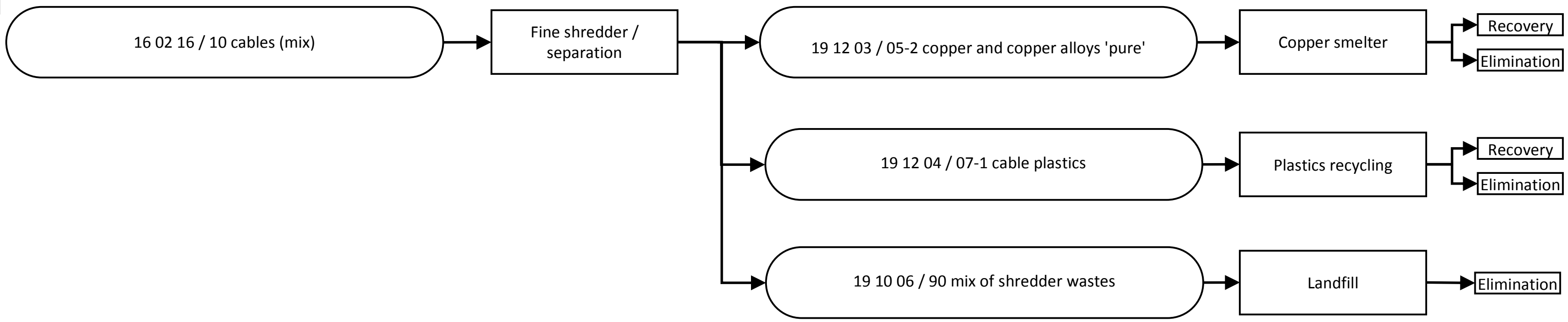


19 12 03 / 04-1 'heavy' non-ferrous metals fraction - 'not pure'
Separation
19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 12 / 03 dismantling/shredder/separation waste - no hazardous substances
Landfill
Elimination

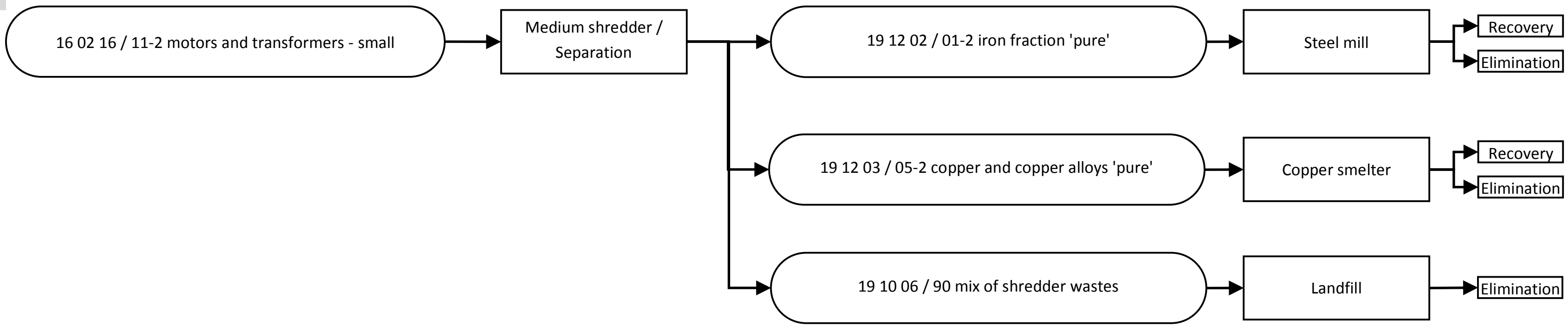
C. Small domestic appliances

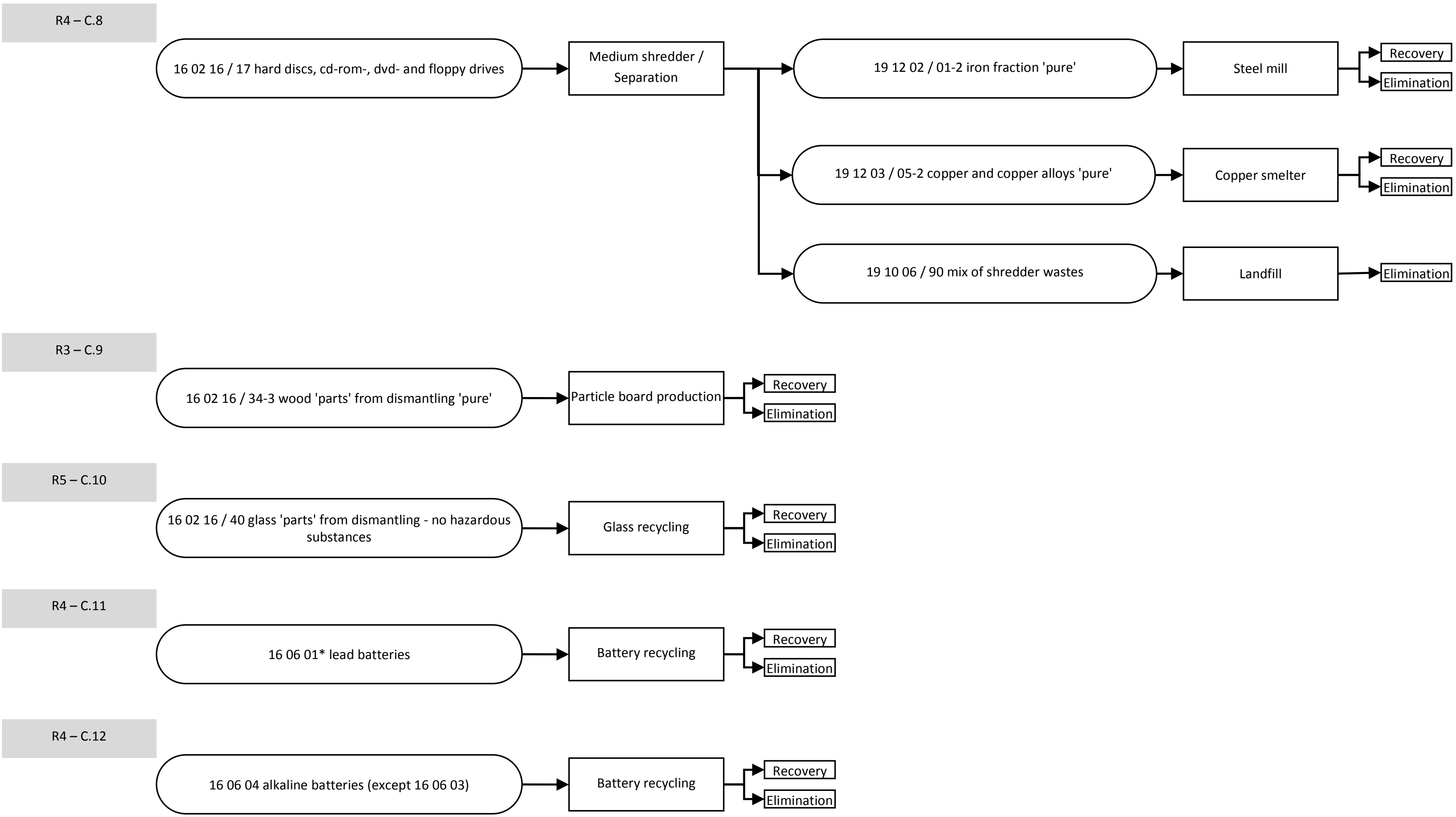

R4 – C.1
16 02 15* / 02-1 printed circuit boards from dismantling - high quality
Other metal smelters
Recovery
Elimination
R4 – C.2
16 02 15* / 02-5 printed circuit boards from dismantling - medium quality
Other metal smelters
Recovery
Elimination
R4 – C.3
16 02 15* / 02-4 power supply units
Medium shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination
R3 – C.4
16 02 15* / 03-1 toner cartridges (mix)
Special treatment of toner cartridges
Recovery
Elimination
R3 – C.5
16 02 15* / 03-2 ink lints (mix)
Special treatment of ink lints
Recovery
Elimination

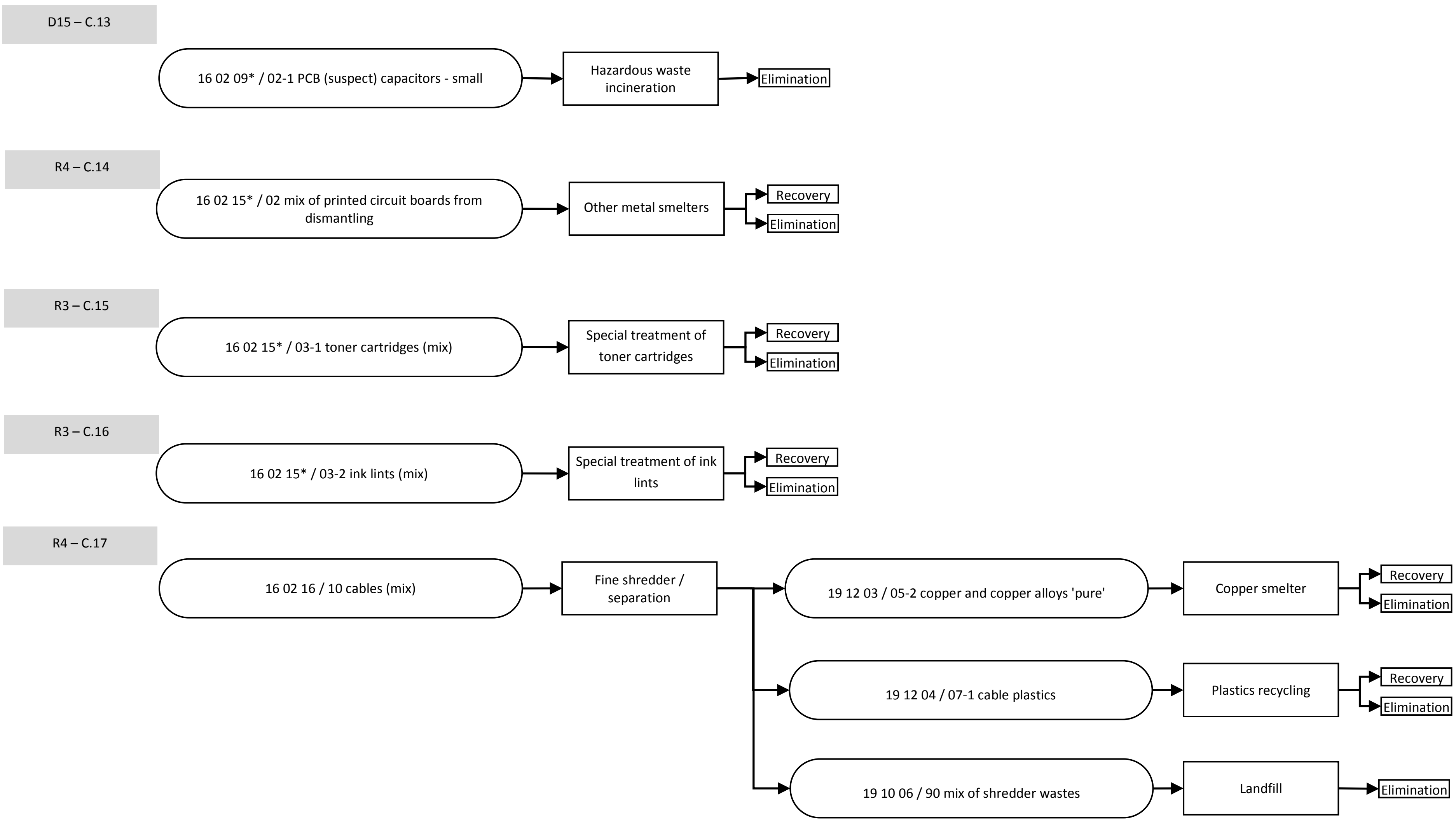
R4 – C.6


16 02 16 / 10 cables (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 04 / 07-1 cable plastics
Plastics recycling
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

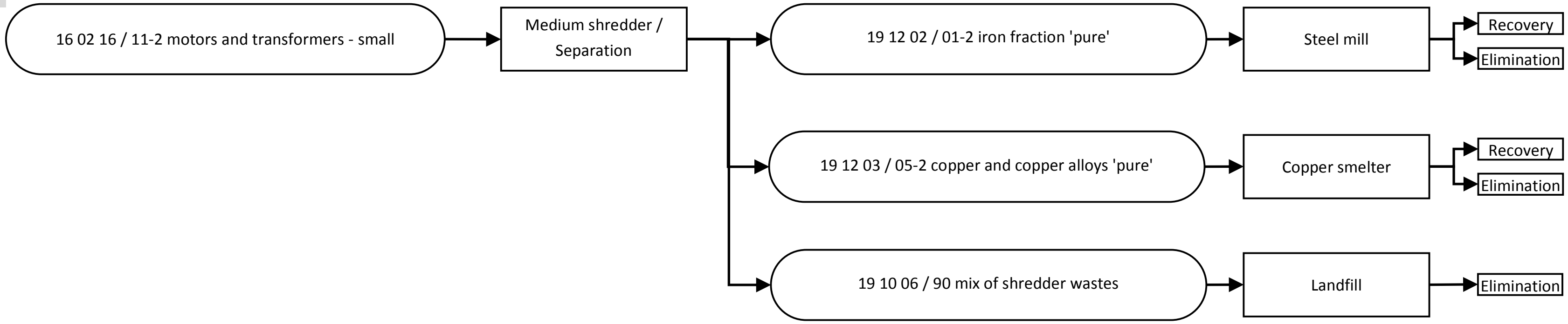
R4 – C.7


16 02 16 / 11-2 motors and transformers - small
Medium shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

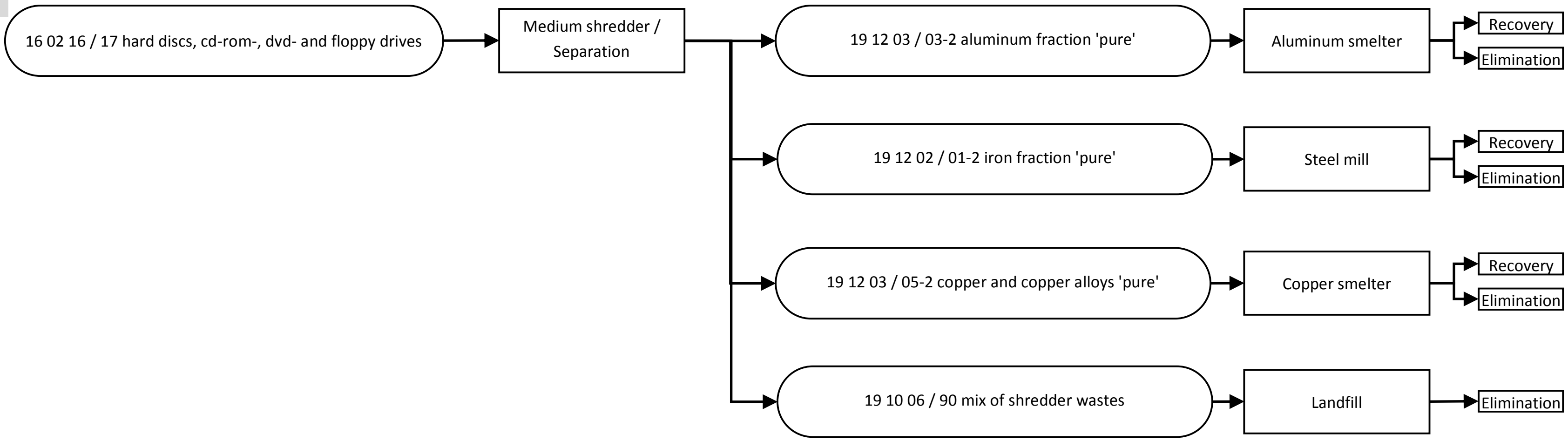

R4 – C.8
16 02 16 / 17 hard discs, cd-rom-, dvd- and floppy drives
Medium shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination
R3 – C.9
16 02 16 / 34-3 wood 'parts' from dismantling 'pure'
Particle board production
Recovery
Elimination
R5 – C.10
16 02 16 / 40 glass 'parts' from dismantling - no hazardous substances
Glass recycling
Recovery
Elimination
R4 – C.11
16 06 01* lead batteries
Battery recycling
Recovery
Elimination
R4 – C.12
16 06 04 alkaline batteries (except 16 06 03)
Battery recycling
Recovery
Elimination


D15 – C.13
16 02 09* / 02-1 PCB (suspect) capacitors - small
Hazardous waste incineration
Elimination
R4 – C.14
16 02 15* / 02 mix of printed circuit boards from dismantling
Other metal smelters
Recovery
Elimination
R3 – C.15
16 02 15* / 03-1 toner cartridges (mix)
Special treatment of toner cartridges
Recovery
Elimination
R3 – C.16
16 02 15* / 03-2 ink lints (mix)
Special treatment of ink lints
Recovery
Elimination
R4 – C.17
16 02 16 / 10 cables (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 04 / 07-1 cable plastics
Plastics recycling
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

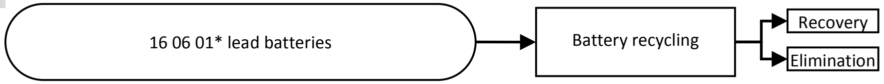
R4 – C.18


16 02 16 / 11-2 motors and transformers - small
Medium shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

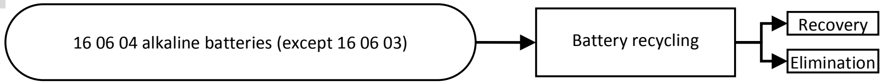
R4 – C.19


16 02 16 / 17 hard discs, cd-rom-, dvd- and floppy drives
Medium shredder / Separation
19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

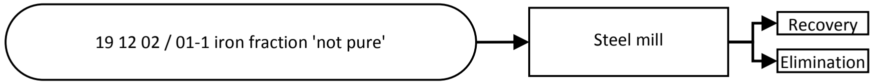
R4 – C.20



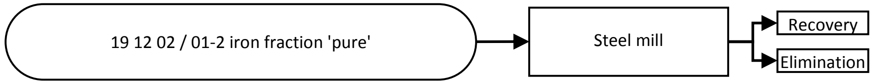
R4 – C.21



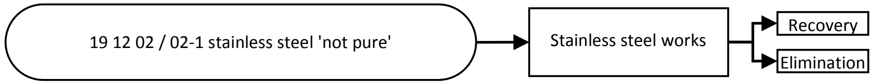
R4 – C.22



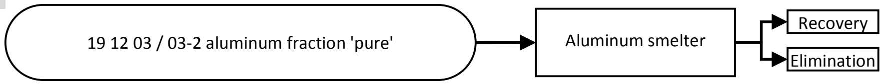
R4 – C.23



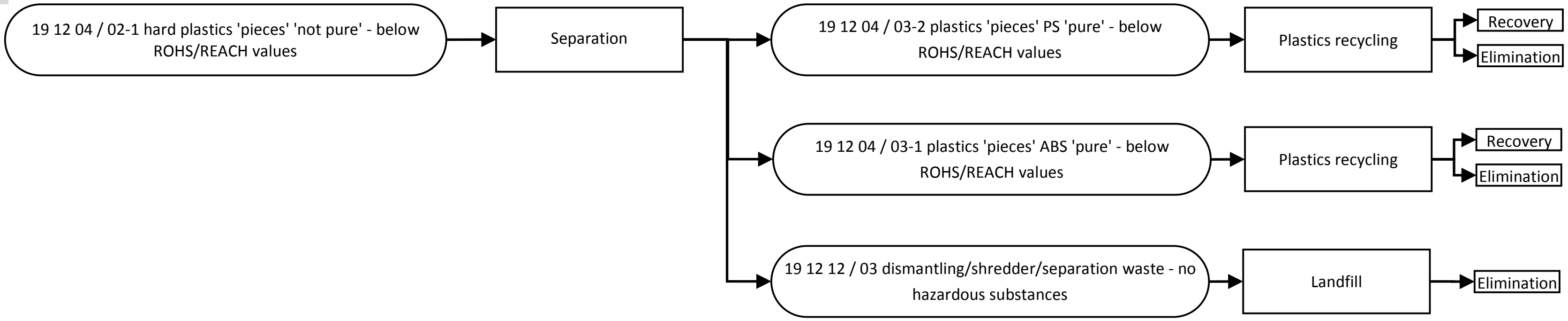
R4 – C.24



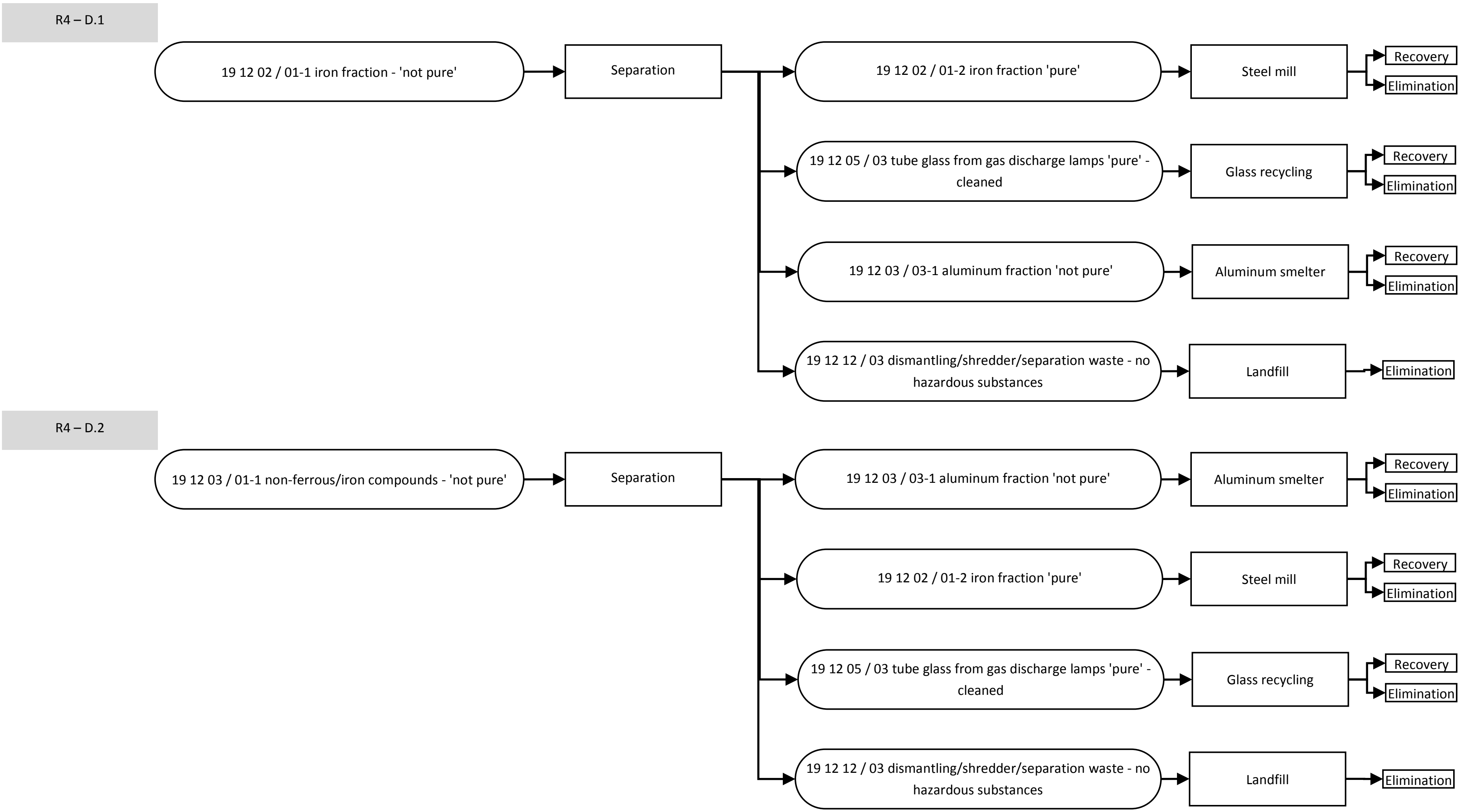
R4 – C.25


19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination

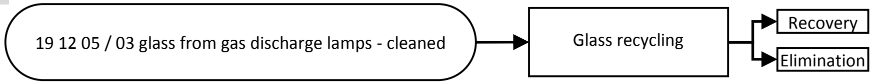
R3 – C.26


19 12 04 / 02-1 hard plastics 'pieces' 'not pure' - below ROHS/REACH values
Separation
19 12 04 / 03-2 plastics 'pieces' PS 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination
19 12 04 / 03-1 plastics 'pieces' ABS 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination
19 12 12 / 03 dismantling/shredder/separation waste - no hazardous substances
Landfill
Elimination

D. Gas discharge lamps

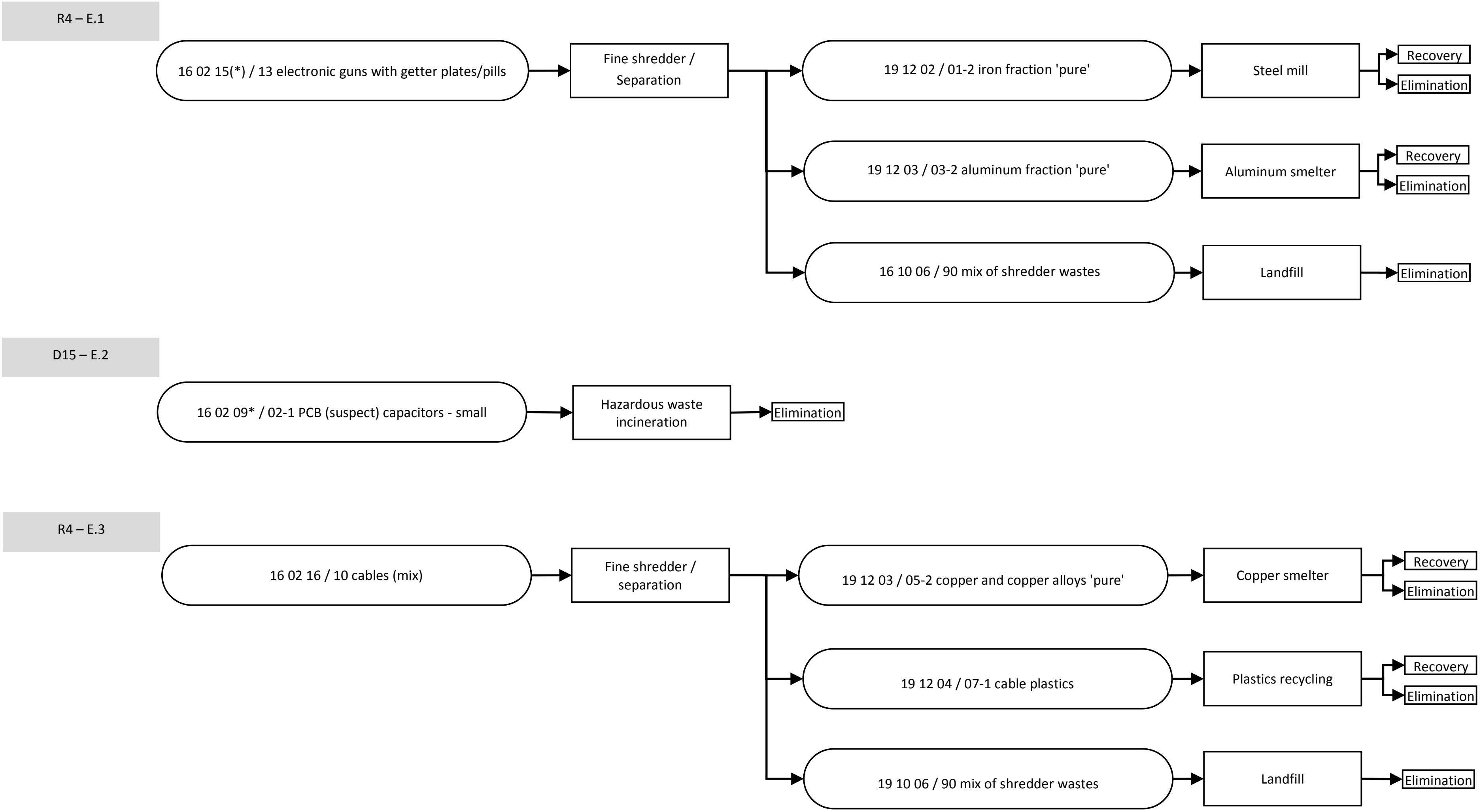

R4 – D.1
19 12 02 / 01-1 iron fraction - 'not pure'
Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 05 / 03 tube glass from gas discharge lamps 'pure' - cleaned
Glass recycling
Recovery
Elimination
19 12 03 / 03-1 aluminum fraction 'not pure'
Aluminum smelter
Recovery
Elimination
19 12 12 / 03 dismantling/shredder/separation waste - no hazardous substances
Landfill
Elimination
R4 – D.2
19 12 03 / 01-1 non-ferrous/iron compounds - 'not pure'
Separation
19 12 03 / 03-1 aluminum fraction 'not pure'
Aluminum smelter
Recovery
Elimination
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 05 / 03 tube glass from gas discharge lamps 'pure' - cleaned
Glass recycling
Recovery
Elimination
19 12 12 / 03 dismantling/shredder/separation waste - no hazardous substances
Landfill
Elimination

R4 – D.3

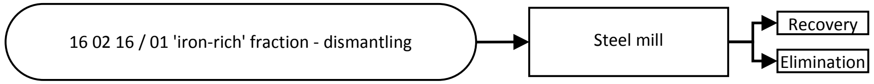


19 12 05 / 03 glass from gas discharge lamps - cleaned
Glass recycling
Recovery
Elimination

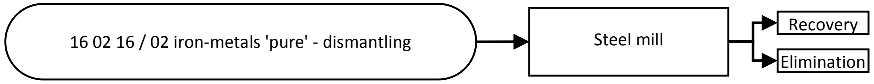
E. CRT televisions and monitors


R4 – E.1
16 02 15(*) / 13 electronic guns with getter plates/pills
Fine shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination
16 10 06 / 90 mix of shredder wastes
Landfill
Elimination
D15 – E.2
16 02 09* / 02-1 PCB (suspect) capacitors - small
Hazardous waste incineration
Elimination
R4 – E.3
16 02 16 / 10 cables (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 04 / 07-1 cable plastics
Plastics recycling
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination

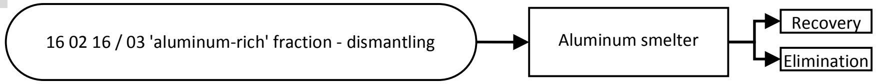
R4 – E.4



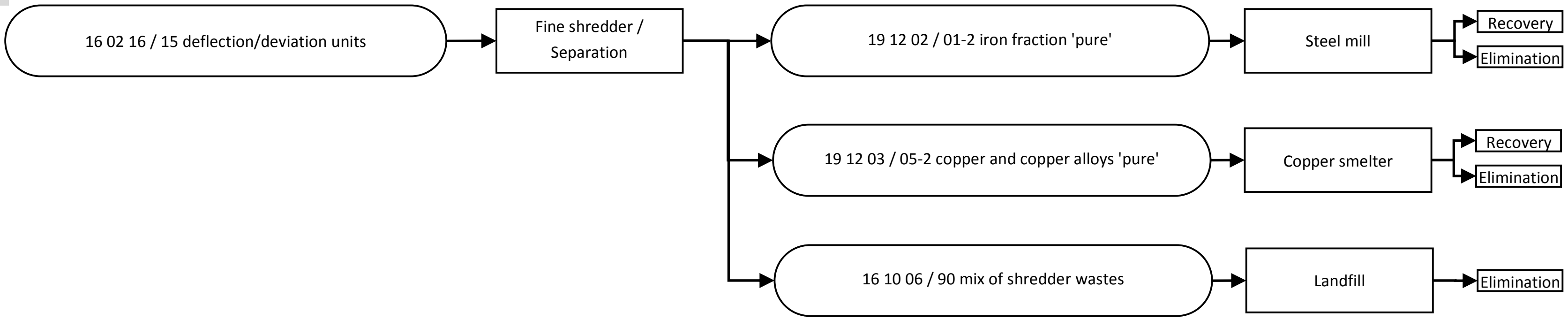
R4 – E.5

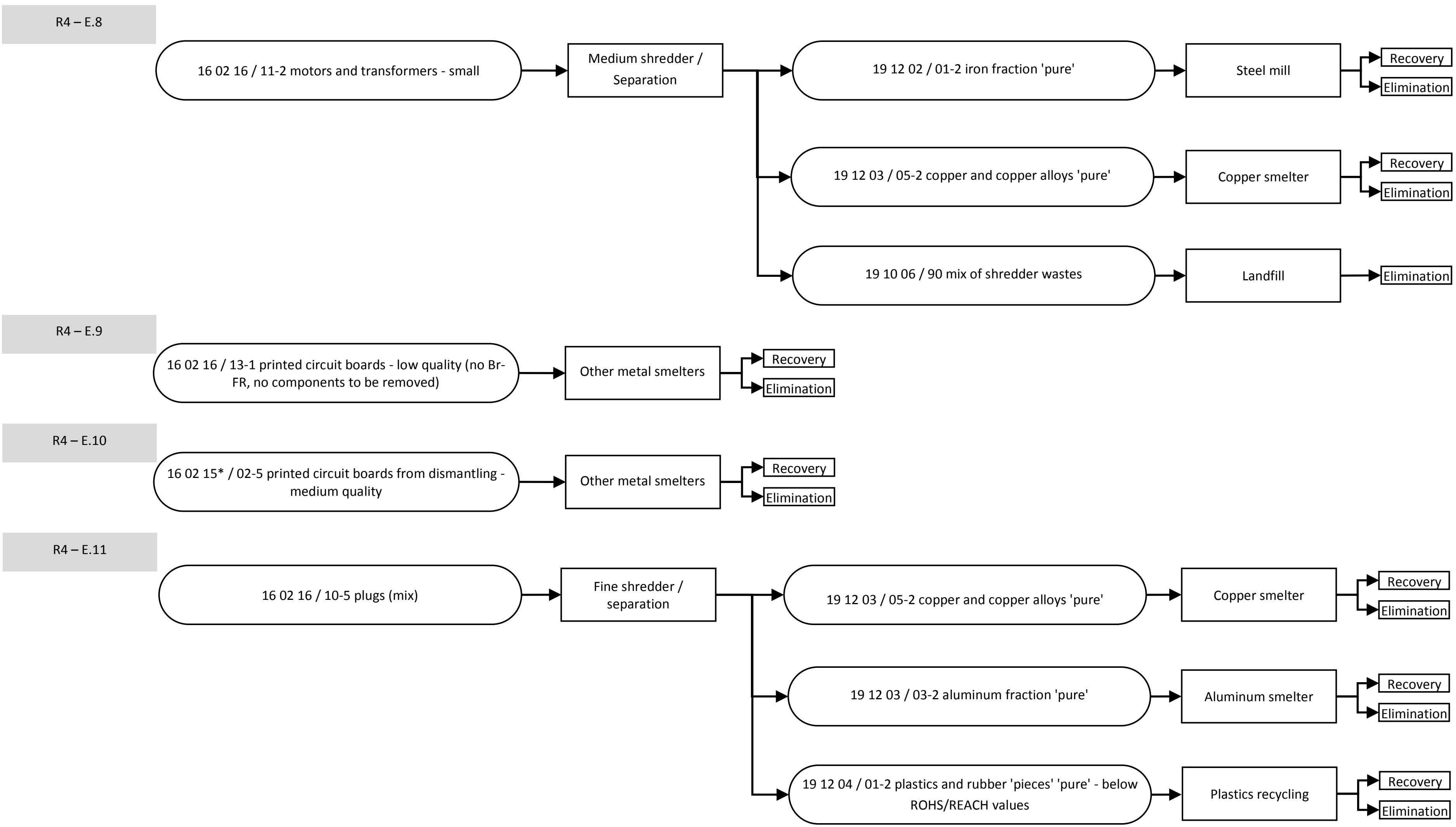


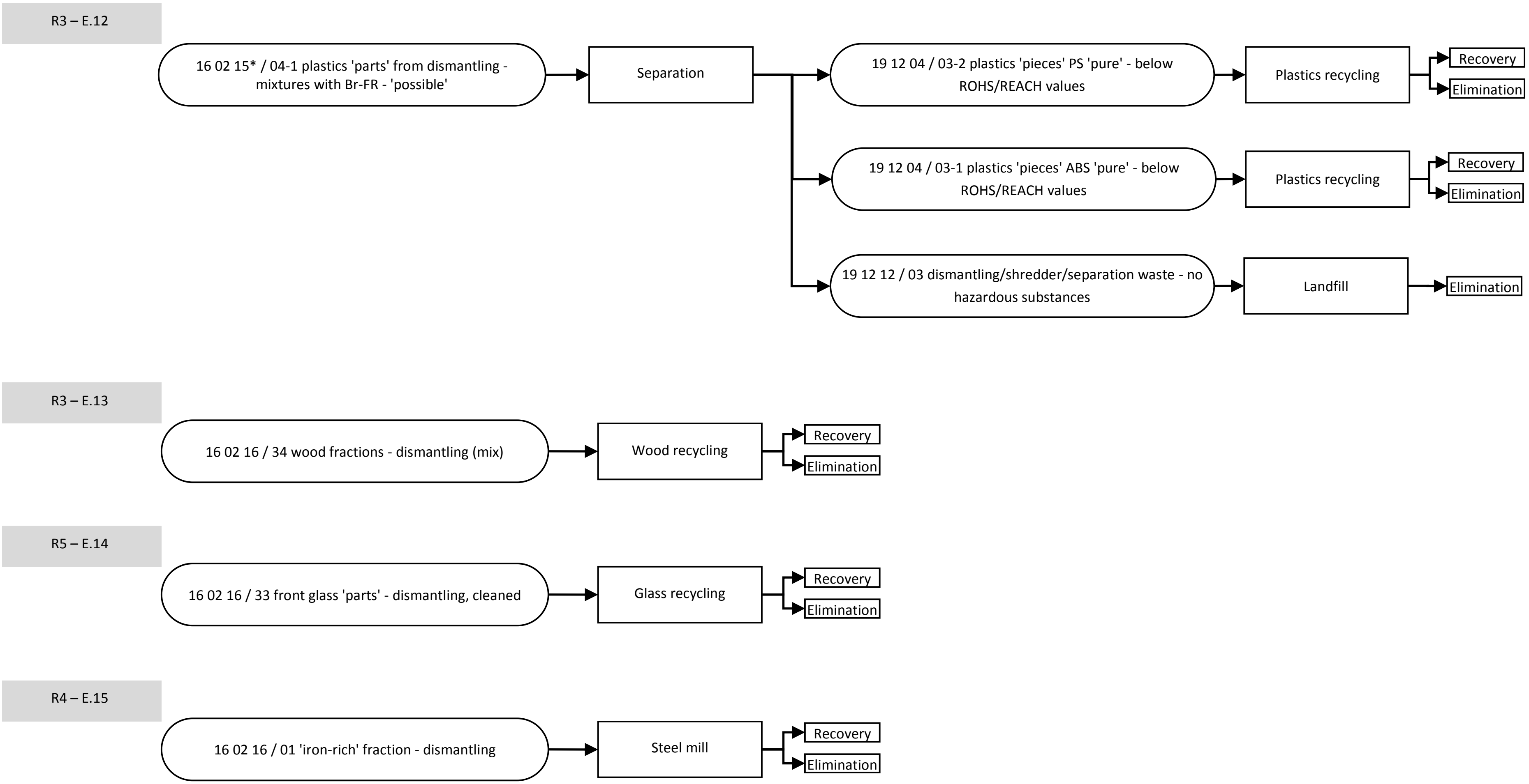
R4 – E.6



R4 – E.7




R4 – E.8
16 02 16 / 11-2 motors and transformers - small
Medium shredder / Separation
19 12 02 / 01-2 iron fraction 'pure'
Steel mill
Recovery
Elimination
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 10 06 / 90 mix of shredder wastes
Landfill
Elimination
R4 – E.9
16 02 16 / 13-1 printed circuit boards - low quality (no Br-FR, no components to be removed)
Other metal smelters
Recovery
Elimination
R4 – E.10
16 02 15* / 02-5 printed circuit boards from dismantling - medium quality
Other metal smelters
Recovery
Elimination
R4 – E.11
16 02 16 / 10-5 plugs (mix)
Fine shredder / separation
19 12 03 / 05-2 copper and copper alloys 'pure'
Copper smelter
Recovery
Elimination
19 12 03 / 03-2 aluminum fraction 'pure'
Aluminum smelter
Recovery
Elimination
19 12 04 / 01-2 plastics and rubber 'pieces' 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination



R3 – E.12
16 02 15* / 04-1 plastics 'parts' from dismantling - mixtures with Br-FR - 'possible'
Separation
19 12 04 / 03-2 plastics 'pieces' PS 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination
19 12 04 / 03-1 plastics 'pieces' ABS 'pure' - below ROHS/REACH values
Plastics recycling
Recovery
Elimination
19 12 12 / 03 dismantling/shredder/separation waste - no hazardous substances
Landfill
Elimination
R3 – E.13
16 02 16 / 34 wood fractions - dismantling (mix)
Wood recycling
Recovery
Elimination
R5 – E.14
16 02 16 / 33 front glass 'parts' - dismantling, cleaned
Glass recycling
Recovery
Elimination
R4 – E.15
16 02 16 / 01 'iron-rich' fraction - dismantling
Steel mill
Recovery
Elimination

Annex III. Mathematical formulation of the dynamic stock model

Generic model

The socioeconomic metabolism and the relation between the inputs and outputs has an dynamic of its own. Because the metabolism of a given product or material can be quite long, in many cases this fact may generate a time laps between the consumption of resources and the emissions of waste.

In this context, dynamic models were developed that correlate the production of waste (outputs) and the magnitude of resources consumption (inputs) and the remaining stock of products and materials in the economy. The example of such models that was used in the research work is given by Elshkaki *et al.* (2005) with the reformulation by Domingos (2008).

The modelling of outputs of waste from the economy is made using two distinct mechanisms, the stock delay mechanism and the leaching mechanism, and these are indirectly affected by the reuse and recycling of products and materials.

<u>Stock delay mechanism</u>

The delay mechanism represents the "unload" of products and is influenced by the respective life time (that depends on the technical characteristics of the products and also of the characteristics of their consumption, technology cycles, etc.) (Elshkaki *et al.,* 2005).

For products with a small life time, the inputs in the system quickly generate the respective outputs. On the other hand, for products that remain for longer periods of time in the economy, the differences between the inputs and the outputs in a given year can be quite different. This fact raises relevant questions in terms of the design and management of systems to deal with the waste.

The equation that describes the mechanism is the following:

Equation A.III.1 – Stock delay mechanism

$$F^{out}(t) = F^{in}(t - L) \qquad \textit{with } t > L$$

Where F^{out} describes the outputs of goods in period *t*, F^{in} corresponds to the inputs and *L* is the life time of the good.

Besides the life time, in order to calculate the production of waste based on the inputs of materials in the past, it is also important to consider the way in which the products reach the end-of-life during the period of analysis considering the entire pool of products that is being used in the economy. In this context, the use of distribution functions is critical to express the probability of a given product that was introduced in the market in time t reaching the end-of-life and becoming waste in time t+n.

According with Melo (1999) and Elshkaki *et al.* (2005) the distribution functions most adequate to describe the dynamic of products in the economy are the Weibull, Beta and Normal distributions. In contrast with the Normal distribution, the other ones can assume different shapes which are likely to occur in practice (Melo, 1999).

In terms of manipulation, the Weibull distribution is preferable to the Beta distribution and it fits better to many types of products (Melo, 1999 and Elshkaki *et al.*, 2005). However, it has been demonstrated that the Beta distribution can be used successfully in modelling de distribution of the end-of-life of some products. Vehicles are one example, as Amaral and Ferrão (2006) showed that the distribution of the end of life of vehicles is a Normal distribution in many countries (Amaral and Ferrão, 2006).

Leaching mechanism

The leaching mechanism refers to the dissipation of the substances that occurs in products during their life cycle (Elshkaki *et al.,* 2005).

Some examples of these types of emissions there is the leaching of heavy metals as a results of corrosion of metallic products or the loss of mass in tires during the use as a result of the tire ware. The amount of emissions is related with the magnitude of the stock and a leaching coefficient can be established to represent this process. In the model by Elshkaki *et al*. (2005) the equation that describes the leaching mechanism is the following:

Equation A.III.2 – Amount of emissions

$$F^{out} = CS(t)$$

Where *S* describes the size of the stock in period *t* and *C* is the leaching coefficient.

The leaching coefficients are difficult to determine but studies have been conducted on this matter and some values can be found in literature. Table A.III.1 presents some examples.

Table A.III.1 – Leaching coefficients

Material / Product	Leaching coefficient (% of mass per year)	Average life time (years)	Source
Rubber (in tires)	0.04[(1)]	3	Valorpneu, 2002
Metals (copper tubing)	0.00035	50	CML, n.a.

Note: (1) Considering a loss of mass of 12.5% and an average life time of 3 years (Valorpneu, 2002)

In order to calculate the stock in period t, an initial amount is necessary to determine for a period t-1, by using the following formula:

Equation A.III.3 - Stock

$$S\,(t) = S\,(t-1) + F^{in}\,(t-1) - F^{out}\,(t-1)$$

Reuse

The activities of reuse influence the evolution of the stock. Considering the approach by Elshkaki *et al.* (2005), the reuse and recycling are modelled considering a fraction of the total inputs using the following equation:

Equation A.III.4 – Reuse

$$R\,(t) = \alpha\,.\,F^{out}\,(t)$$

Where R(t) is the amount of materials reused in period *t*, *α is the reuse/recycling rate and* F^{out} are the outputs from the system.

General equation to quantify the material outputs

Considering the mechanisms previously described, in order for the model to go by the law of mass conservation, because S is reduced along the time with leaching (Domingos, 2008), the generic equation that allows to estimate the outputs from the inputs is as follows:

Equation A.III.5 – Material outputs

$$\frac{\partial S}{\partial t} = F^{in}(t) - e^{CL}F^{in}(t-L) - CS(t) + \alpha F^{out}(t)$$

With which:

Equation A.III.6 – Material returns to the environment

$$F^{out}(t) = e^{CL}F^{in}(t-L) + CS(t) - \alpha F^{out}(t)$$

Where F^{out} represents the materials returned back to the environment.

In special cases where C=0, because there is no loss of mass along the products life cycle, or for motives of simplification of the use of the model, the leaching mechanism may not be considered and the mathematical formulation becomes:

Equation A.III.7 – Material returns to the environment, when leaching effect is null

$$F^{out}(t) = F^{in}(t-L) - \alpha F^{out}(t)$$

Model used in the management of WEEE

Considering the specificities of the management of WEEE, and the characteristics of electrical and electronic equipment and the data that was available for the research work, the following assumptions were used when applying the stock dynamic model previously described:

Delay mechanism

To estimate the amount of WEEE generated in a given year, it was considered the inputs from the data available from AMB3E (2005) with data series dating back from 1994, in some cases. The availability of such long time series of data is critical because some electrical and electronic equipment have high average life times.

The distribution used to determine the probability with which the equipment reach the end-of-life was the Weibull, which is widely used in studies for the same purpose (see National Institute for Environmental Studies, 2011). The distribution can be characterized by the following equation, for x>0:

Equation A.III.8 – Delay mechanism

$$f(x,k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}}$$

Where λ is the scale parameter and is > 0 and k is the shape parameter and is also > 0.

For each type of electrical and electronic equipment several distinct bibliographic data was used to determine these parameters, namely the one available in the Lifespan database for Vehicles, Equipment, and Structures, of the National Institute for Environmental Studies (NIES) of Japan.

Leaching mechanism

Due to the characteristics of the electrical and electronic equipment in general, it was considered that no leaching existed and so no mass loss was considered during the use phase.

Reuse

Because there is not enough data on the amounts of discarded electrical and electronic equipment that are repaired and reused in Portugal this effect was not considered in the analysis. The possible error induced by this assumption should be small as despite the lack of

data, the general perception of the PRO’s and specialists is that the reuse is a practice with little application.

Limitations

The distortion factors also occur during periods of small sales volumes, because users keep their products for longer periods of time, in some cases over their normal expected life time, which originates a reduction of the amounts of WEEE generated. This may be increasingly relevant in the current days of the economic crisis, where sales volumes are being reduced.

Other examples of factor that influence the estimation of the production of WEEE are the second hand market, for used products, and the users that do not discard their old equipment.