Louvain School of Management
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Profit-driven planning and analysis of a WEEE recycling facility with a multi-period MILP model

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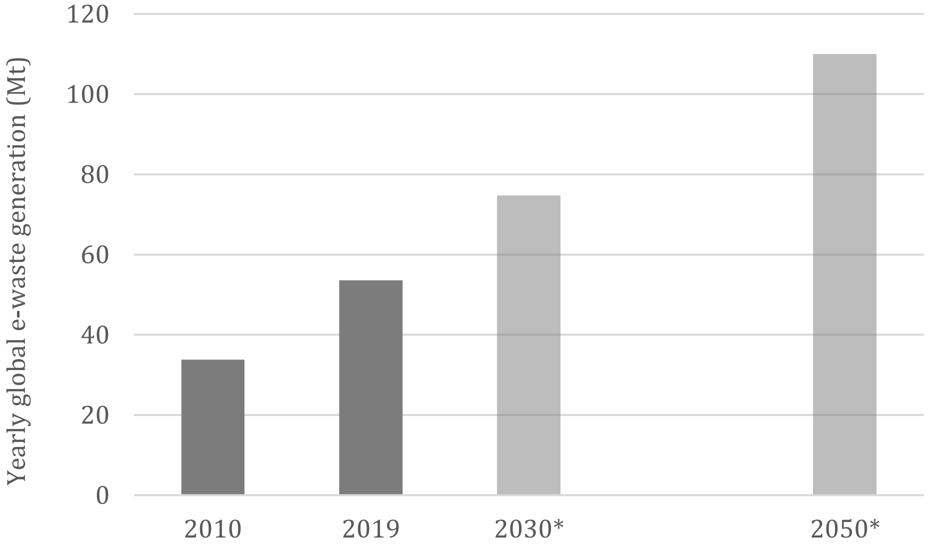
Acronyms

EEE	Electrical and Electronic Equipment
EOL	End Of Life
EOQ	Economic Order Quantity
EPR	Extended Producer Responsibility
EU	European Union
E-waste	Electronic waste
MILP	Mixed Integer Linear Program
MIP	Mixed Integer Program
RL	Reverse logistics
SC	Supply Chain
SCM	Supply Chain Management
TBL	Triple bottom line
WEEE	Waste Electrical and Electronic Equipment

Part 1: Introduction

1.1. The problem of e-waste

In 2019, the world generated over 53Mt of e-waste[1] (Baldé et al., 2020), a surge of almost 60% from 2010. With a yearly increase between 3 and 5%, e-waste is one of the fastest-growing waste streams (Koshta et al., 2021; Tsai et al., 2009; Baldé et al., 2022), and estimates project a doubling by 2050 (Baldé et al., 2022), as shown on Figure 1.



* Values for 2030 and 2050 are estimates

Figure 1 - Global e-waste generation (Baldé et al., 2014; Baldé et al., 2020)

This impressive growth of e-waste can be explained by the mixed effects of a growing demand for consumer electronics combined with shorter replacement cycles (Sadeghi, 2019). The former effect is the result of increasing population and urbanization (Dixit et al., 2016), a widespread ownership of multiple ICT devices (Malekkhouyan et al., 2012), the emergence of a global middle class, and the increasing disposable income in many developing countries (Baldé et al., 2017). The latter is caused by low prices, the ease to purchase new products and hassle (time, logistics and cost) to repair old ones leading to quick disposal of, often times, functional devices (Agarwal et al., 2012), and obsolescence caused by rapid developments in technology (Malekkhouyan et al., 2021; Lau et al., 2009,

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[1] Note that we use the terms e-waste and WEEE interchangeably throughout this work.

Capraz et al., 2015) and increasing product versatility (Alves et al., 2021) as well as fashion-oriented expectations and environmental and legislative drivers (Capraz et al., 2015).

There are significant discrepancies between regions, however, with the level of development and the amount of e-waste generated per capita being positively related, as seen in Table 1. With the highest amount of e-waste generated per capita, Europe, and more particularly the EU, has the responsibility to be at the forefront of WEEE collection and recycling by leveraging its innovative capacities and legislative power.

Table 1 – E-waste generation by continent and per capita in 2019 (Baldé et al., 2020)

	Africa	Americas	Asia	Europe*	Oceania	World
E-waste generated (Mt)	2.9	13.1	24.9	12	0.7	53.6
E-waste generated per capita (kg/inh)	2.5	13.3	5.6	16.2	16.1	7.3

*Including Russia

Starting with the WEEE directive in the EU in 2003, governments all around the world have implemented laws on product take-back and recycling of e-waste, based on the concept of EPR (Gui, 2020; Atasu et al., 2012), where producers are responsible for the EOL management of their products. While 71% of the world's population was covered by national e-waste policy, legislation, or regulation in 2019, legislation does not necessarily come with enforcement and only around 17% of the globally generated e-waste was documented to be collected and properly recycled (Baldé et al., 2020). In the EU, the recycling rate was around 40% in 2020 with Belgium slightly below average at 38.6% (European Parliament, 2023), leaving room for improvement to reach the 65% collection target of 2019 (Directive 2012/19/EU).

There is a need for further awareness on the urgency of recycling WEEE, which has become the most critical and vital economic and environmental challenge facing the world in the waste department (Malekkhouvan et al., 2021).

WEEE contains hazardous substances and polluting agents that are a threat to the environment and to public health (Agarwal et al., 2012; Dixit et al., 2016; Kazancoglu et al., 2020; Malekkhouyan et al., 2021; Capraz et al., 2015; Lau et al., 2009). Improper handling of heavy metals such as lead, mercury, cadmium, and chromium as well as other substances such as halogenated substances, plastics, and brominated flame retardants can impair human health, from respiratory problems to cancer (Hanafi et al., 2008) and cause environmental pollution. For example, one mobile phone battery contains enough cadmium to contaminate 600 000 liters of water (Capraz et al., 2015). Additionally, recycling metals can contribute to a reduction in CO2 emissions, by substituting these recycled materials for virgin materials for which the extraction, refinement, and transport are much more CO2 intensive. For instance, the recycling of iron, aluminium, and copper contributed to a net saving of 15 MT of CO2 in 2019 (Baldé et al., 2020).

Concerning the economic aspect, e-waste is often referred to as an 'urban mine' as it contains several rare and expensive materials, in a higher concentration than in mines. These valuable materials such as gold, silver, copper, palladium, and others can be recovered and reused if managed properly (Kostha et al., 2021), representing a significant economic opportunity (Singh et al., 2022; Widmer et al., 2005). Baldé et al. (2020) estimated the total value of raw materials in e-waste in 2019 at €57 Billion, with iron, copper and gold contributing the most. Other than raw materials, valuable components and parts can also be recovered and re-used in manufacturing.

Because of these environmental and economic considerations, it is crucial to understand how the recycling of WEEE can be stimulated and what the main challenges and threats are to making the RL processes of e-waste efficient, cost-effective, and environmentally sound, such that collection and recycling targets can be met in a responsible manner.

1.2. Motivation

We were initially attracted to RL because it is a field of SCM that has become increasingly important these past years, primarily fueled by environmental concerns and the move towards a circular economy. As such, RL was the perfect field for us to address concepts and knowledge relevant both to our SCM major at the Louvain School of Management and to our Energy, Natural Resources, and the Environment major at the Norwegian School of Economics.

The issue of e-waste was not one we were very familiar with, but we were eager to work on it given its originality for a master thesis.

1.3. General structure and working methods

In this work, we used a mix of qualitative and quantitative methods to gather information and conduct analyses. It is organized into six parts:

Part 1 – Introduction. In this part, we provide a first glimpse into the problem of e-waste based on articles and papers found online and cover the main motivations and methods related to this work. We also outline our research objectives and the limits associated with them.

Part 2 – Supply Chain Management and electronic waste. This part consists of a review of general concepts relevant to the topic at hand, namely the RL of e-waste.

Part 3 - Literature review. In this part, a formal review of literature concerning the RL of e-waste is performed using a strict methodology, to present a comprehensive analysis of existing research on the topic, leading to the formulation of our research objectives.

Part 4 – Model. The purpose of this part is to describe the specificities of WEEE recycling in Belgium based on several reports and on the website of Recupel, as well as explaining the processes of an e-waste recycling plant. In line with these descriptions, we then propose an MILP mathematical model which serves as a tool for the analysis.

Part 5 – Analysis. In this part, we translate the mathematical model into the optimization software AIMMS to test different scenarios and carry out further analysis on selected elements. The aim is to provide useful information and recommendations for the operation of a WEEE recycling plant.

Part 6 – Conclusion. In the conclusion, the main results and findings from the analysis are highlighted. Then, a discussion on the implications of these results for researchers and industry professionals, followed by the limitations of the work, and recommendations for future research conclude this work.

1.4. Research objectives and limits

The objectives we pursue in this thesis are multiple. First, we aim to build a multi-period MILP model for the planning of a WEEE recycling plant in Belgium with a profit maximizing objective, based on scientific literature, and adapted to the Belgian situation. This model is to be representative of reality while not being overcomplicated, such that the most relevant and important aspects affecting the profitability of an e-waste recycling plant can be analyzed in a reasonable amount of time. The second objective of this thesis pertains to the analyses using the proposed model. We seek to provide helpful insights through sensitivity analyses on the model and its parameters, to identify and evaluate some of the factors that can significantly impact the profitability and viability of recycling WEEE.

Overall, this thesis is relevant to anyone interested in the e-waste recycling process. The findings can be valuable to policymakers, industry stakeholders, researchers, and individuals seeking to contribute to the sustainable management of e-waste.

However, it is important to acknowledge certain limitations of this thesis. Firstly, the absence of real case data to anchor the model in reality may restrict the accuracy and applicability of the findings, potentially limiting their relevance. Additionally, the model serves the only purpose of optimizing the planning of the recycling facility, without considering outside effects, such as varying market parameters and the behavior of other recycling agents, Recupel, or customers, which can have significant impacts on prices, quantities collected, and more. Moreover, the deterministic nature of the model might be an oversimplification, and the robustness would be increased with stochastic modelling. Nevertheless, this would most likely heavily impact the complexity, and thus the run time of the model, limiting the range of analyses possible. Finally, we do not dive into the art of finding stronger formulations to the model, to keep it intuitive.

Part 2: Supply Chain Management and electronic waste

This part aims to provide the necessary information to comprehend the general concepts at hand in this thesis, based on scientific articles, reports and other publications. We start in section 2.1. with SC, SCM and SC planning followed by RL in section 2.2. and WEEE in section 2.3. This prepares the ground for the formal literature review in part 3.

2.1. Supply Chain Management

The term “Supply Chain” (SC) appeared in 1982 with Olivier and Webber, and gained popularity in the 1990s (Asgari, 2016; Hugos, 2018). Initially, SC was defined as “a group of organizations engaged in various processes that provide value by creating products and services for end customers, with interconnected organizations cooperating through upstream and downstream linkages to manage and improve the flow from suppliers to end-users” (Stadtler, 2015). Later, Mentzer et al. (2001) defined SC as “the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the SC, for the purposes of improving the long-term performance of the individual companies and the SC as a whole.” Finally, Mentzer et al. (2001) argue that the SC includes all activities involved in the transformation of raw materials into finished goods and their delivery to end customers.

The term “Supply Chain Management” (SCM) was first mentioned in 1982 (Stadler, 2014). A current definition of SCM is given by Bowersox et al. (2019), who state that SCM is “a set of processes aimed at effectively and efficiently integrating suppliers, manufacturers, distribution centers, distributors and retailers.” The terms effectively and efficiently refer to the fact that this set of processes should ensure that products are produced and distributed in the right quantities, to the right locations and at the right time to minimize system costs, while achieving the desired value proposition for the consumer. Simchi-Levi et al. (2000), and Mentzer et al. (2001) argued that effective SCM requires a focus on optimizing the entire SC, rather than just individual functions. Moreover, Iyer, et al. (2009) as well as Mentzer et al. (2001) emphasize the importance of coordination, collaboration, integration, and agility in effective SCM, which is crucial for developing effective strategies for managing risk and uncertainty.

Finally, Stadtler & Kilger (2010) define SC planning as “the process of developing and implementing strategies to manage the flow of goods, services, and information across the supply chain”. Effective SC planning can help organizations to improve their performance, reduce costs, increase efficiency, and enhance customer satisfaction (Chopra & Meindl, 2016). The authors note that effective SC planning requires a deep understanding of customer needs, supplier capabilities, and internal processes. In a similar vein, Stadtler & Kilger (2010) highlight the importance of SC planning in achieving customer satisfaction and improving SC performance.

2.2. Reverse Logistics

2.2.1. Definitions

RL is not a recent concept. In the past, resource scarcity drove people's actions to restore and recover products. However, with the advent of inexpensive materials and advanced technology, societies began to engage in mass consumption and disposal of products without regard for the environment.

In the 1970s, the Club of Rome's research indicated that there were limits to growth, prompting the need for sustainable development. In the following decade, environmental disasters drew the attention of societies, leading to widespread awareness and the adoption of practices like recycling or reuse, making RL an increasingly important subject. Finally, in the mid-1990s, Europe began enforcing legal regulations on product and material recovery or proper disposal (De Brito & Dekker, 2004).

RL can be associated with different definitions through time. In 1992, Stock defines RL as “the role of logistics in recycling, waste disposal, and management of hazardous materials, which also includes logistics activities related to source reduction, recycling, substitution, reuse of materials, and disposal”. In 1993, Kopicky also includes reverse distribution, which relates to the flow of goods and information in the opposite direction of normal logistics activities. Finally, in 1998, The ‘European Working Group on Reverse Logistics’, define RL as “the process of planning, implementing, and controlling flows of raw materials, in-process inventory, and finished goods, from a manufacturing, distribution, or use point to a point of recovery or point of proper disposal” (De Brito & Dekker, 2004).

These definitions indicate that RL includes a wide variety of processes and flows. These are simplified and summed up by Tsai et al. (2009) for a waste RL system in Figure 2.

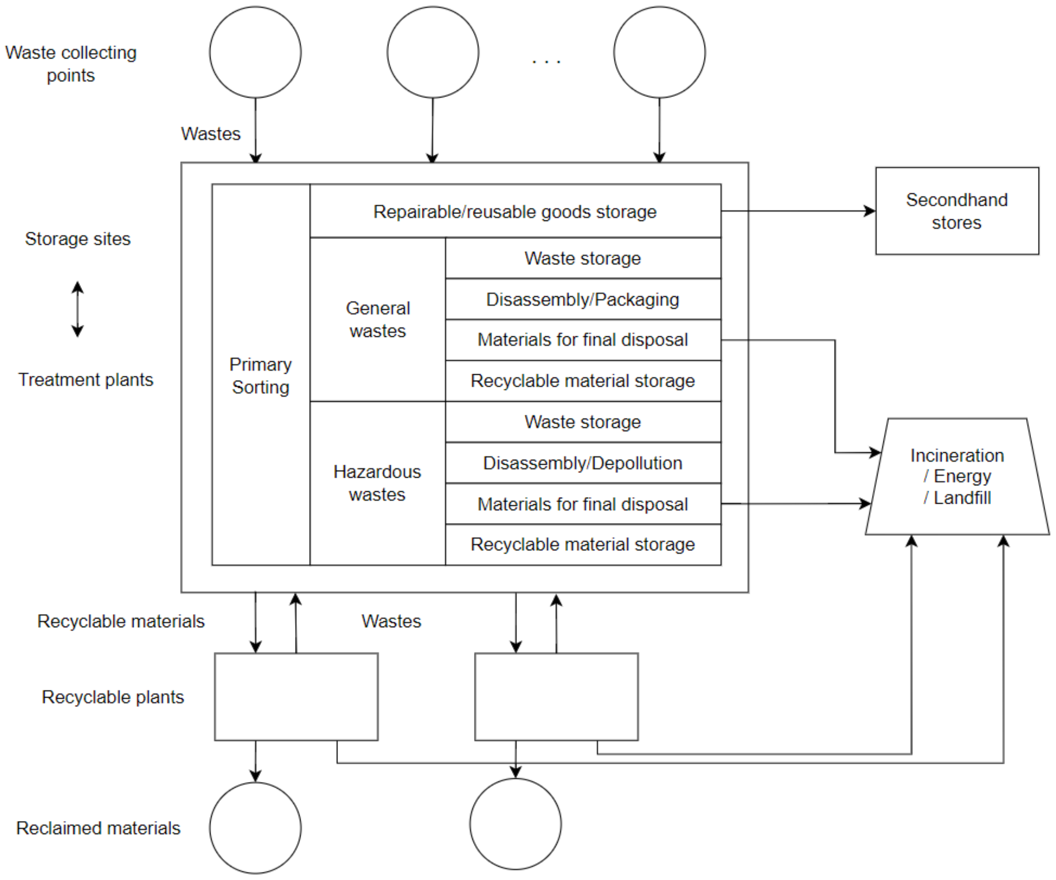
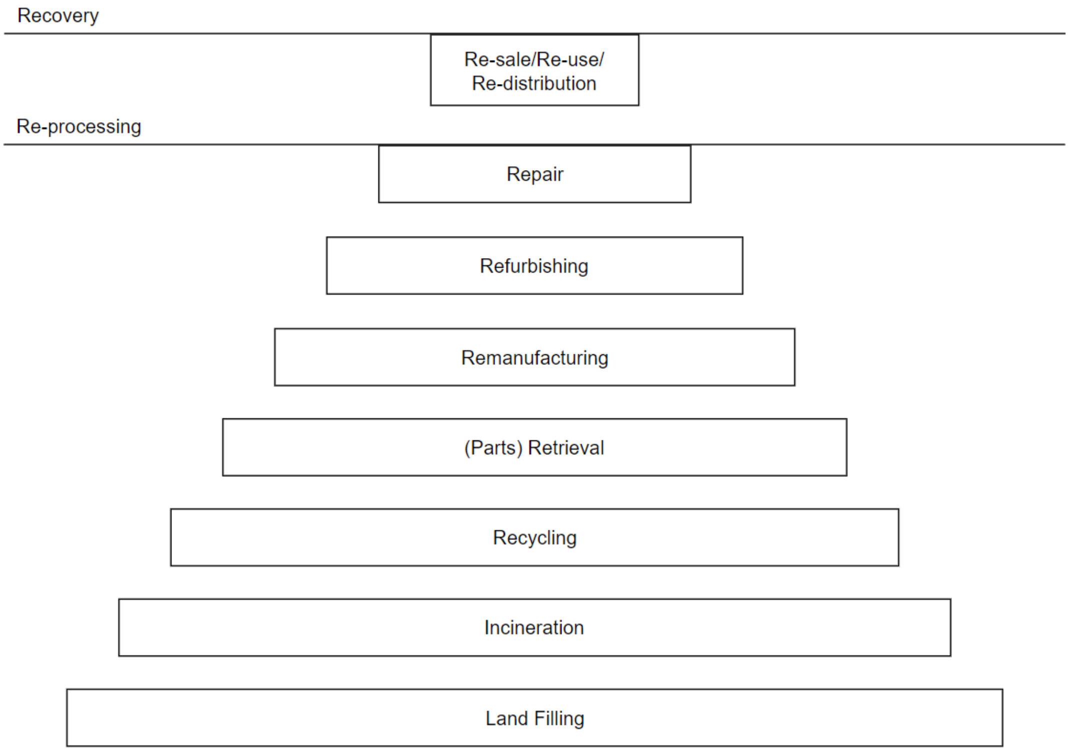


Figure 2 - Simplified waste RL system (Tsai et al., 2009)

2.2.2. Recovery

There are different types of recovery processes in RL, such as product recovery (re-sale, re-use, re-distribution, repair, and refurbishing), component recovery (remanufacturing and parts retrieval), material recovery (recycling), and energy recovery (incineration) (De Brito & Dekker, 2004). In product recovery, products can be re-used in their original market or in a secondary market, while component recovery involves dismantling products and re-using their components in the manufacturing of the same or different products. Material recovery requires additional processing to retrieve materials from products (such as metals and plastics), which are then re-used in manufacturing. Finally, products that aren’t re-used or recycled are incinerated for energy recovery, whereby burning the product releases heat that is captured for different purposes such as district heating. Products that are not processed at all often end up in landfills. Figure 3 below represents the typical hierarchy of the RL recovery options, based on their environmental friendliness. Generally, the less a product must be processed the better, as this means less resource and energy usage.



*Options go from most preferred (lowest environmental impact) to least preferred (highest environmental impact) from top to bottom

Figure 3 – RL recovery options pyramid (De Brito & Dekker, 2004)

2.2.3. Sustainability

RL can be considered as a component of sustainable development, which aims to fulfill present needs without jeopardizing the ability of future generations to fulfill their own. Therefore, RL is part of the TBL frame and is important in achieving sustainable SCM in the circular economy transition. The TBL concept provides a framework for organizations to integrate social, environmental, and economic considerations in their decision-making and performance evaluation. By balancing these three dimensions, organizations can achieve long-term sustainable growth (Elkington 1998), improve their financial performance (Gond et al., 2017), and contribute to a more sustainable and equitable world (Lozano, 2015). RL also refers to the 3R system, which stands for Reduce, Reuse, and Recycle (Zhang et al., 2022).

In fact, the effective implementation of RL management practices can help organizations to minimize their environmental impact and contribute to the development of a circular economy by reducing waste and conserving resources (Stock & Mulki, 2009), which can also help them recover value and improve customer satisfaction (Rogers & Tibben-Lembke, 1999).

2.3. Waste Electrical and Electronic Equipment

Waste Electrical and Electronic Equipment (WEEE) refers to a wide variety of products that are thrown away after use (European Parliament, 2023). Formally, any equipment dependent on electric currents or electromagnetic fields in order to work properly is considered EEE, falling into one of the ten categories covered in the EU WEEE directive (2012/19/EU):

1. Large household appliances (Refrigerators, freezers, washing machines, electric stoves, air conditioning appliances, etc.)
2. Small household appliances (Vacuum cleaners, irons, toasters, fryers, clocks, scales, electric toothbrushes, etc.)
3. IT and telecommunications equipment (printers, personal computers (PC) including keyboard, mouse and screen, calculators, fax machines, telephones, etc.)
4. Consumer equipment and photovoltaic panels (radio sets, television sets, video cameras and recorders, etc.)
5. Lighting equipment
6. Electrical and electronic tools (drills, sewing machines, welding and soldering tools, etc.)
7. Toys, leisure and sports equipment (electric trains or car racing sets, video games, hand-held video game consoles, computers for biking, etc.)
8. Medical devices
9. Monitoring and control instruments (smoke detectors, thermostats, etc.)
10. Automatic dispensers (for hot drinks, money, solid products, etc.)

According to the European Parliament (2023), of the total WEEE collected in the EU in 2020, 52.7% were large household appliances, 14.6% consumer equipment and photovoltaic panels, 14.1% IT and telecommunications equipment, 10.1% household appliances and 8.4% other. Figure 4 below shows what these proportions were in Belgium in 2021 for EEE collected by Recupel (photovoltaic panels not included).

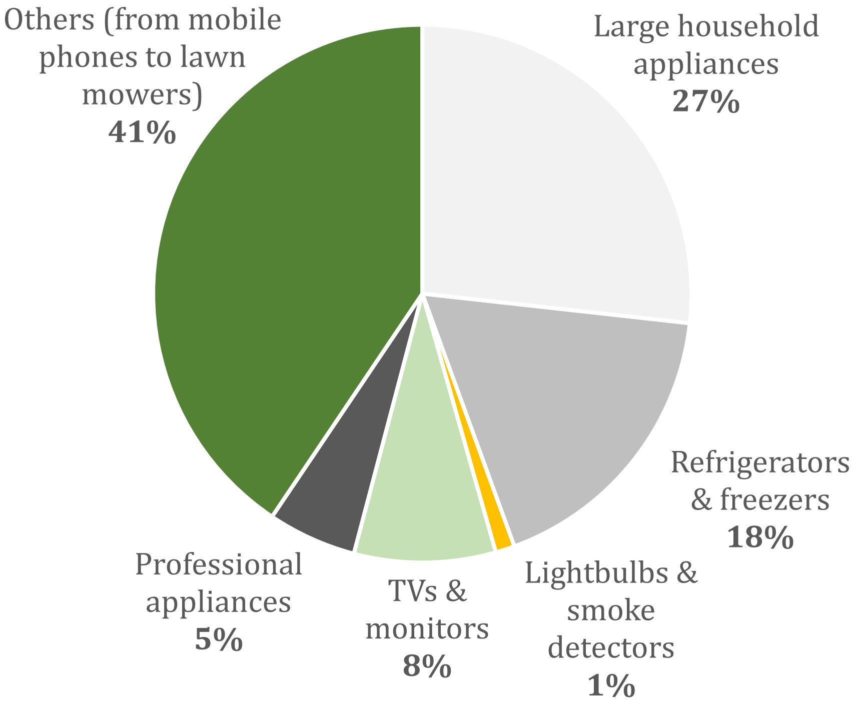


Figure 4 – WEEE collected in Belgium by Recupel in 2021 by category (% of total weight) (Recupel, 2021)

Part 3: Literature review

In this part, we perform a systematic exploratory literature review of the RL of e-waste, starting with the methodology in section 3.1. followed by the review divided thematically into five sections (3.2. to 3.6.) covering all the areas of research identified. Following this review, we identify an area for further research in section 3.7.

3.1. Methodology

This systematic literature review was carried out using a method with five steps.

1. Online databases were searched using specific keywords and selection criteria to retrieve relevant articles. These keywords were “Reverse logistics”, “Returns management”, “E-waste”, “Electronic waste”, “Sustainability”, and “Triple-bottom-line”, and the criteria for selection of articles included publication dates after the year 2000, exclusion of press releases, availability of full text, and peer-reviewed articles. A total of 992 articles were collected from the following databases: ABI/Inform Collection (202), ScienceDirect (509), EBSCO (61), Emerald Management 125 (146) and Scopus (74).
2. Duplicates were sorted and removed from the retrieved articles. This was done by comparing the articles with each other and removing those that were identical or very similar in content. A total of 83 duplicates were removed.
3. The articles were sorted based on their relevance to the topic through screening of their titles and abstracts. A total of 786 articles were removed.
4. A deeper analysis of the selected 123 articles was performed to evaluate their relevance and reliability. Articles from a journal with SJR indicator < 1 were removed, eliminating 80 of them. Higher SJR indicator values are meant to indicate greater journal prestige and reliability.
5. The information collected from the remaining 43 articles was synthesized and categorized into relevant themes, namely ‘Drivers and barriers’ (2.2.2.), ‘Consumer behavior’ (2.2.3), ‘Coordination’ (2.2.4), ‘Forecasting returns’ (2.2.5.), and ‘MI(L)P models’ (2.2.6.). This was done by reading each article in detail and evaluating the methods, results, and conclusions. This provided a foundation for the structure of the literature review and allowed for a comprehensive overview of the topic.

3.2. Drivers and barriers

Several authors (Börner et al.,2018; Rizos et al., 2022) have highlighted the drivers and barriers of the implementation of RL for e-waste in different countries through the categories of policy, financial/economic factors, SC, technology, consumer/society, and business organization. Börner et al. (2018) developed a framework that provides four conditions for successful e-waste governance characterized by EPR i.e., inclusion of all stakeholders, overall strategic collaboration, adequate rule system, and knowledge sharing/performance management. Furthermore, Lau et al. (2009) examined whether current RL theories and models from developed countries can be fully applied in developing countries such as China, and Guarnieri et al. (2016) investigated how to consider the divergent views of stakeholders to implement e-waste RL in Brazil, taking into account the economic, environmental, and social aspects established by the NPSW (National Policy on Solid Waste). Finally, Lau et al. (2009) conducted action research (AR) to create and implement an e-waste management program in line with the NPSW regulation.

The results of Lau et al. (2009) suggest that while the drivers for RL vary from company to company, the barriers to RL are common and are mainly external. The main difficulties identified for the implementation of RL in the electronics industry in developing countries such as China are the lack of applicable laws, regulations, or guidelines to motivate manufacturers, the lack of economic support and preferential tax policies, low public awareness of environmental protection, and the underdevelopment of recycling technologies. Finally, Lau et al. (2009) highlighted the need for public awareness of e-waste disposal, as public awareness has led to a significant increase in the amount of waste collected.

3.3. Consumer behaviour

Multiple authors (Argarwal et al., 2012; Dixit et al., 2016; Kochan et al., 2016; Kamal et al., 2022) have carried out research with the aim of determining the psychological determinants of the intention to return e-waste. Argarwal et al. (2012) went deeper into the topic and sought to understand consumer return behavior of EOL products at different incentive levels by proposing a scenario in which return is initiated by a policy of returning low-cost damaged or non-functioning products that are either out of warranty or not under warranty while promoting environmental sustainability. Then, authors such as Koshta et al. (2021) investigated the end-users' willingness to pay (WTP) for the recycling of the e-waste they produce. Dixit et al. (2016) and Koshta et al. (2021) used the Theory of Planned Behavior (TPB), Kochan et al. (2016) used the Theory of Reasoned Action, Argarwal et al. (2012) used a particle swarm optimization (PSO) algorithm, and Kamal et al. (2022) conducted a study to examine the type of information that influences consumers' intention to return e-waste immediately to small and medium-sized enterprise manufacturers based on social marketing theory. The results of the different studies suggest that attitudes, behavioral control, environmental awareness, standards, and convenience are significant predictors of return intention and behavior (Gonul Kochan et al., 2016; Dixit et al., 2016), as well as consumer WTP for waste recycling (Koshta and al., 2021). Kamal et al. (2022) suggested that in addition to this, knowledge of product return also positively influences consumers' environmental attitudes and pro-environmental behavior, i.e. the immediate return of e-waste. Finally, the research results of Dixit et al. (2016) show that return intention acts as a mediating variable in predicting return behavior.

Finally, another group of authors (Mansuy et al., 2020) analyzed which attributes of collection services consumers prefer, whether the type of product has an impact on preferences, and whether there are significant differences in the population. They conducted a survey in Brussels, where collection rates for EEE are lower than in other Belgian regions. The results identify price as the attribute with the greatest impact on the choice of a collection service. Secondly, preferences for a collection service depend strongly on the type of product, highlighting the heterogeneous nature of WEEE. Thirdly, income, occupation, and household structure are the main predictors of consumer preferences.

3.4. Coordination

Some authors have investigated the competition and coordination environment in the RL environment of e-waste. Li et al. (2017) investigated four coordination strategies and performed a comparative analysis on the optimal decisions of different models among different parties in a three-echelon reverse SC consisting of a single collector, a single remanufacturer, and two retailers with complete information sharing. Sadeghi et al.

(2019) also investigated competition and coordination problems between channels as well as chains in the RL environment when the chains have different policies for their reverse channel. Moreover, Sadeghi et al. (2019) aimed to investigate what the optimum values of the discounts are when a chain selects a centralized or decentralized structure and how optimum values and members' profit change in the presence of a coordination contract. Both Li et al. (2017) and Sadeghi et al. (2019) proved that maximum profitability and recycle quantities, i.e. the economic and social benefits, occur when chains select the centralized case. Moreover, Sadeghi et al. (2019) proposed a wholesale price contract to coordinate a member's decision when the recycling fee of the reverse chain acts as the wholesale price in forward logistics.

Moreover, different authors have investigated the different forms of producer responsibility in e-waste recycling and their consequences. Atasu et al. (2012) investigated the implications of collective and individual producer responsibility (CPR and IPR) models of product take-back laws for e-waste on manufacturers' design for product recovery choices and profits, and on consumer surplus in the presence of product competition. Gui (2020) studied if a collective form of EPR implementation where producers may jointly invest in recycling facilities could promote their incentives to do so by developing a Nash bargaining model that captures the decision dynamics underlying joint recycling facility investment. Finally, Börner et al. (2018) developed a framework that has brought four successful conditions for e-waste governance characterized by EPR (inclusion of all stakeholders, overall strategic collaboration, an adequate rule system, and knowledge sharing/performance management). Atasu et al. (2012) and Gui (2020) showed that IPR offers superior design for product recovery (DfR) incentives as compared to CPR and provides a level of the competitive ground because CPR may distort competition and allow free riding on DfR efforts to reduce product recovery costs.

Finally, Simpson et al. (2010) investigated practices used by manufacturing firms to recycle their more heterogeneous secondary materials that arise through the RL channel and waste management practices by exploring the potential for interaction or networking between members of a SC to create 'recycling relationships' that generate new markets or disposal solutions for recyclables. The study proposes new areas of inquiry into the benefits of information sharing to increase the opportunities for profitable recycling between collocated organizations.

3.5. Forecasting returns

Predicting the quantities of WEEE is important in RL because it helps to plan and manage the collection, transport, and processing of this waste more efficiently. Ayvaz et al. (2014) proposed a grey forecasting system to forecast return product quantity in the RL network. Hanafi et al. (2008) presented another effective collection strategy that considers cost and environmental impact simultaneously; an integrated collection strategy that combines a Fuzzy Colored Petri Net forecasting method and collection network model to collect EOL products. The integrated collection strategy developed found that by providing demographic data and historical sales of a relevant product in a certain location, the best strategy to collect EOL products in that location can be determined via good forecasts.

3.6. MI(L)P models

Many authors (Kumar et al., 2019 ; Kumar et al., 2022; Özkır et al., 2012 ; Keyvanshokooh et al., 2013. ; Govindan et al., 2020 ; Malekkhouyan et al., 2021 ; Tsai et al., 2009 ; Shokohyar et al., 2013 ; Capraz et al., 2015 ; Safdar et al., 2020) have modeled RL of e-waste using a MILP. While Özkır et al. (2012) pursued cost minimization and profit maximization as their sole objective, the other authors pursued several objectives through their models. Özkır et al. (2012) described the features of a green SC in which the recovery process occurs in three different ways: material recovery, component recovery, and product recovery. The aim of its model was to inform managers about the opportunities of enhancing product returns in terms of quality and quantity. The most interesting conclusion generated by this study is that any change in the quantity of returned products has more effect on the profitability of the closed-loop SC network than any change in its quality.

The first sub-objective pursued by some authors (Keyvanshokooh et al., 2013 and Capraz et al., 2015) concerns the pricing decision. Keyvanshokooh et al. (2013) addressed the problem of designing and planning a multi-echelon, multi-period, multi-commodity and capacitated integrated forward/reverse logistics network model to consider a dynamic pricing approach for used products, forward/reverse logistics network configuration, and inventory decisions. The major contribution of this research was determining the acquisition price for these valuable products according to their quality level. Based on this determined price, it calculates the percentage of potential returned products as well.

Capraz et al. (2015) presented a model to determine the maximum bid price offer for a recycling facility while determining the best operation planning strategies to be profitable. The results show that the bid price should be kept as low as possible when the fluctuations of prices are higher.

The second sub-objective developed by other authors (Govindan et al., 2020 and Tsai et al., 2009) is supplier selection. Govindan et al. (2020) presented a model concerning an inventory-location-routing problem developed for circular supplier selection and order allocation in a multi-product circular closed-loop SC considering multi-depot, capacitated green routing problem using heterogeneous vehicles that deal with imposed uncertainties. Tsai et al. (2009) focused on the treatment and recycling system and proposed a two-stage (treatment and recycling) multi-objective decision framework. In the treatment stage, the responsible producer selects treatment suppliers under EPR. Then is the recycling stage in which the decision-maker plans the reclaimed material production. The results show that the ranking of suppliers is more stable than the quantities allocated to suppliers under different priority structures.

The third objective pursued by Kumar et al. (2019 ; 2022), and Shokohyar et al. (2013) was to design a model to determine the best locations for collection centers and also recycling plants for the total management of WEEE. Kumar et al. (2019) developed a unique three-phase, multi-period multi-product model to optimize the problem of selecting optimal locations while accounting for CO2 emissions while Kumar et al. (2022) formulated a model to minimize the total and embedded cost to the carbon footprint in which installation location decisions are optimized. Additionally, Kumar et al. (2019; 2022) took into account the selection of the appropriate vehicle type for transportation in each arc between facilities along the reverse SC, again incorporating vehicle CO2 emissions. The novelty of Kumar et al.'s (2022) research lies in the development and application of an exact solution method, namely "Improved Benders Decomposition" to find a quality solution in a reasonable time. Its results claim that the choice of vehicle fleet affects the decision of location in the network and significantly reduces the carbon footprint. Shokohyar et al. (2013) included not only the environmental aspect but also the societal aspect by designing a model to determine the best locations for the collection centers and recycling plants for managing the total WEEE amount.

The fourth sub-objective pursued by Safdar et al. (2020) is to build a model for the RL based on the TBL concept. The objectives of the formulated model are to maximize the profit and minimize carbon emissions as well as maximize the job opportunities in a RL network while dealing with uncertainty. The research considers first customers, collection centers, distribution centers, second customers, and reprocessing units consisting of return evaluation centers, recycling centers, and refurbishing centers. The carbon cap-and-trade policy was incorporated into the model.

Other authors (Rogers et al., 2012; Li et al., 2018; Chen et al., 2016; Kazancoglu et al., 2020; Shi et al., 2020; Kannan et al., 2017; Guo et al., 2017; Lu et al., 2006; Rogetzer et al., 2019; Malik et al., 2015) present non-MILP modeling techniques that can be applied to RL problems.

Some authors propose MIP models with different objectives. Shi et al., (2020) optimized the addition of a certain number of new facilities in each period of a market expansion stage to gradually increase the accessibility of the infrastructural collection network. Kannan et al., (2017) determined the optimal allocation of the products on the disassembly lines and the optimal flow of product and components in between the facilities such that the maximum possible revenue can be earned. Then, Lu et al. (2006) aimed to determine what products to accept, process, and reprocess while determining when cleanups are required for discrete materials recovery over time given a particular recycling process design configuration, process capacity, and inventory space capacity. Li et al. (2018) proposed a multi-echelon multi periods and multi-products fuzzy integer nonlinear programming model to maximize the profit incurred in the network through product recovery. The specificity of their model is that the uncertainty in the quantity and quality of the returned products are modeled using fuzzy triangular numbers.

Finally, other modeling techniques were used for other purposes. Chen et al. (2016) formulated a mathematical model based on the EOQ theory to search for the optimal replenishment quantity, the retail price of the product, and the return rate for the used products while minimizing the total related costs for the retailer. Kazancoglu et al. (2020) used a multi-criteria method, i.e., TODIM (Tomada de Decisão Iterativa Multicritério) to achieve sustainability in RL based on a TBL while implementing a method that can be used in decision-making under risk. Guo et al. (2017) proposed a multi-period and dynamic joint construction model to build the multilevel RL network aimed at minimizing the different sources of cost. It verifies the feasibility of the rendered model by adopting the particle swarm optimization (PSO) algorithm and genetic algorithm (GA). Finally, Malik et al. (2015) used Graph Theory and Matrix Approach (GTMA) to model the determination of the location of the collection sites for the recovery of returned products.

3.7. Formulation of the research objectives

Concerning the subsections "Drivers and barriers ", "Consumer behavior", "Coordination" and "Forecasting returns", we can see that these topics have been widely studied in several ways in the literature. Given our academic background and the constraints that come with the writing of a master thesis (primarily timing and financial), it was difficult for us to see how we could have made a real contribution to the literature in these areas.

The category "MI(L)P", is broader and closer to our field of study. Among the different MILP models and issues discussed in this category, be it the general optimization problem, the supplier selection problem, the optimal locations selection problem, or the TBL problem, we see that only Capraz et al. (2015) have focused on the planning of an e-waste recycling plant. They pursue the specific goal of determination of the maximum bid price using a static model, which allowed us to notice a gap in the current literature.

The objectives that we will pursue in this thesis are to:

1. Present a description of the WEEE recycling environment in Belgium and describe the different processes and sources of costs and revenues of a WEEE recycling facility.
2. Present a simple multi-period MILP model for the planning of an e-waste recycling facility following a profit maximization objective.
3. Conduct sensitivity analyses on the model and its parameters to determine what could make or break the profitability of an e-waste recycling facility, and leverage the multi-period aspect of the model to conduct analyses on scenarios where timing and capacities can be limiting factors.

Part 4: Model

In this part, we present our multi-period MILP model in section 4.2. derived from the model by Capraz et al. (2015) after having presented the environment around which it is built in section 4.1.

3.1. Modelling environment

This section provides an overview of the context in which the model is built. It includes the specificities of WEEE collection and recycling in Belgium (4.1.1.), an explanation on the functioning of the proposed recycling facility (4.1.2.), the possible sources of costs and revenues of such facility (4.1.3.) and other assumptions made when building the model (4.1.4.).

4.1.1. Electronic waste recycling in Belgium

In Belgium, Recupel is responsible for managing the collection, sorting, processing, and recycling of WEEE, but also for the financing and reporting on these activities, as well as raising awareness about WEEE recycling. Recupel is a not-for-profit organization founded by Belgian manufacturers and importers in 2001.

New EEE placed on the market is subject to a "recycling fee" in the form of a contribution based on the type of equipment. This contribution, which finances Recupel’s activities, is determined by Recupel every year, taking several factors into account such as the size and complexity of appliances. As of 2023 (Recupel), it ranges (incl. tax) from 0.0121€ for a few categories of small appliances to 10€ for heat pumps, fridges, and boilers. Most of the contributions are at or below 1€, though, except for televisions and monitors (5€ and 1.7€ respectively), thus representing a very small amount when compared to the price of these appliances.

As of 2021, Recupel collects WEEE through the 544 recycling or container parks run by intermunicipal companies and municipalities, and 11 697 collection points at registered retailers and in supermarkets and small hardware stores (Recupel, 2021).

4.1.2. Recycling processes

The management of e-waste involves several steps, namely collection, testing, disassembly, shredding, and separation. We briefly explain the different processes, which are in accordance with EU requirements, as presented by Capraz et al. (2015) and summarize them in Figure 5 below.

The collection of WEEE is done by individuals or organizations that want to dispose of their electronic devices. Many communities have recycling programs that offer drop off locations or pick-up services for e-waste, such as Recupel in Belgium. In some cases, manufacturers or retailers may also offer collection services for their products.

The first step in the e-waste recycling process is testing. During this stage, electronic devices are inspected to determine if they are still functional. Working devices can be refurbished and resold, reducing the amount of e-waste generated. Defective devices are moved on to the next stage of the process. It is important for recyclers to test devices as accurately as possible to ensure that they are not accidentally recycling functional devices.

The next step is disassembly. In this stage, devices are taken apart and separated into individual components. Proper disassembly of electronic devices can be challenging due to the variety of designs and the complexity of some devices. Indeed, different types of electronic devices may require different tools and techniques for disassembly, and it may not be possible to disassemble them simultaneously using the same equipment (Total Green Recycling, 2019). Moreover, it is not recommended to process multiple types of inputs simultaneously during disassembly, as this could lead to the mixing of materials and potentially cause safety issues. Disassembly is mandatory for appliances containing hazardous materials that can contaminate other parts, such as batteries, cartridges, and screens, which must be processed separately (recovered, destroyed, or processed in an environmentally friendly way at authorized companies) (Ahlers et al., 2021). We consider a disassembly process where products containing hazardous substances ('PC', 'LCD TV', 'LCD Monitor', 'CRT TV', 'CRT Monitor')[2] are completely disassembled, allowing for the retrieval and sale of components and parts.

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[2] PC: Personal Computer, LCD: Liquid Crystal Display, TV: Television, CRT: Cathodic Ray Tube

Once all the hazardous substances are removed from the WEEE, the rest is to be shredded. Products that do not contain hazardous substances ('Vacuum cleaner', 'Iron', 'Toaster', 'Kettle', 'Printer', 'Fax machine', 'Video recorder', 'Radio') therefore skip the disassembly stage and are directly shredded if not deemed suitable for direct reuse at the testing stage. During this stage, the electronic components are shredded into small pieces using industrial shredders. This is an important step as it helps to make the separation process easier and more efficient as well as making it easier to store and transport the materials.

The final process in WEEE recycling is separation, which involves separating the different materials obtained from shredding. This process is crucial as it allows for the materials, primarily metals and plastics, to be recovered and reused which can reduce the need for mining and production of new materials, as well as reduce the amount of waste that ends up incinerated or in landfills.

Any rest material from disassembly or separation that isn't hazardous and cannot be re-used is sent out for incineration. Figure 5 summarizes the layout of the proposed recycling facility, showing the arrangement of the main processes and possible flows of products, components, and materials.

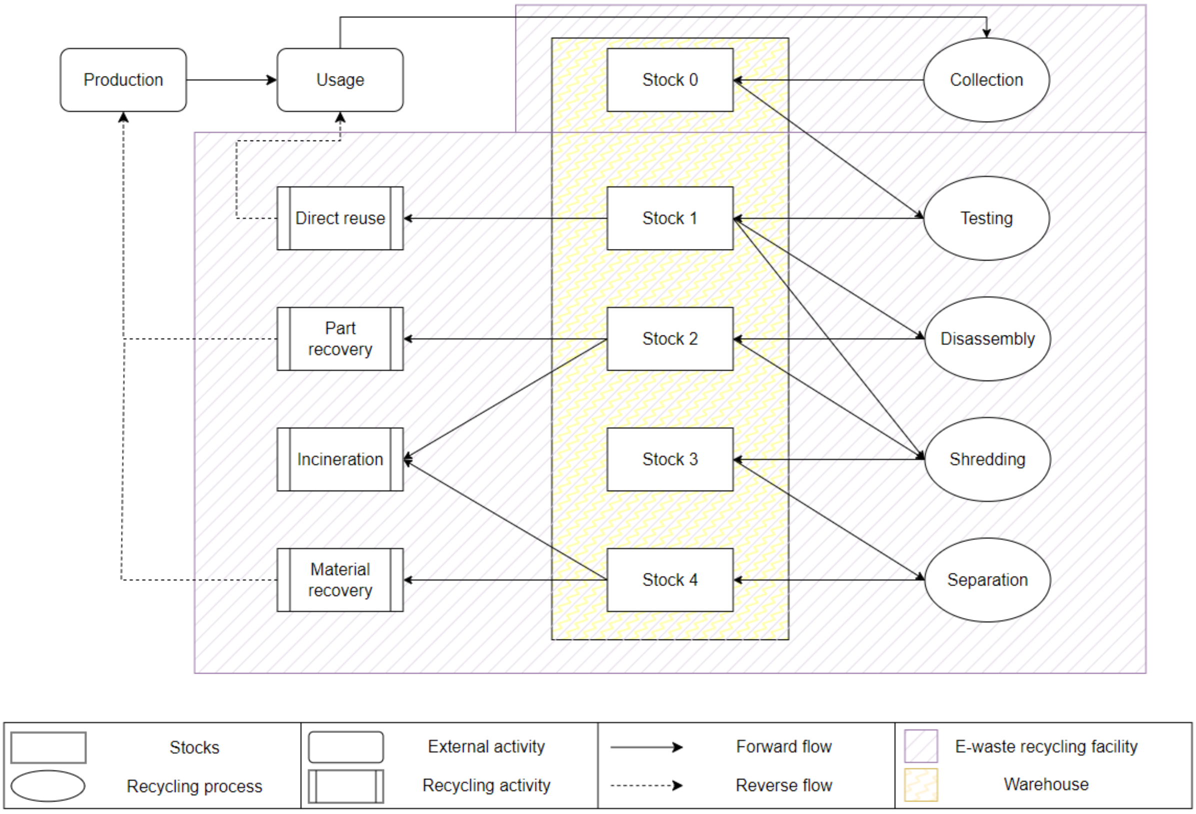

Figure 5 – Overview of the proposed recycling facility's activities and flows

4.1.3. Sources of costs and revenues

Here is a more detailed analysis of the different sources of costs and revenues for an e-waste recycling plant. We explain if and how they are implemented in the model, and Table 2 provides an overview of the considered costs and revenues.

The first type of possible costs are the purchasing costs of e-waste from various suppliers such as businesses, governments, or communities (Karakayali et al., 2007) which may vary depending on the quality and quantity of the waste (Capraz et al., 2015). In our case, we consider a facility that has a contractual agreement with Recupel to properly recycle a certain amount of WEEE, for which it is compensated. The facility receives batches containing a variety of products and must process them as a whole. The compensation is based on the Recupel recycling contribution, thus dependent on which products are processed.

The second source of costs are transportation costs, which may vary depending on the distance between the supplier and the plant, as well as the volume and weight of the waste (Singh et al., 2022). For simplification's sake, transportation costs are ignored. However, the high recycling capabilities in Belgium along with its small size reduce the need for long-range transport, reducing logistical costs, and the transport between collection points and recycling operators is managed by Recupel anyways (Ahlers et al., 2021).

Other than fixed costs, which cover the overall operation of the plant (Capraz et al., 2015), the proposed facility also incurs labour, holding, and processing costs. Labour is notoriously expensive in Belgium, and we consider a fixed number of employees with possible overtime. These employees are to be assigned daily to one of the processes that require personnel (Capraz et al., 2015; Cui & Forssberg, 2003): batch reception, testing, disassembly, or preparation for sale or incineration. Holding costs may vary depending on available facilities and environmental regulations in force (Singh et al., 2022), but in our case, we consider a constant holding cost. Finally, processing costs associated with testing and disassembly workstations, as well as bulk recycling units (shredders and separators) (Capraz et al., 2015) are considered. While these may vary depending on technologies and methods used (Stuart & Christina, 2003; Dalrymple et al., 2007), we use a fixed value for each station.

The first source of revenues concerns the sale of valuable raw materials, such as rare metals, and plastics. (Capraz et al., 2015; Singh et al., 2022; Widmer et al., 2005; Malekkhouyan et al., 2021). The second one concerns the sale of recycled products, such as electronic components, spare parts, and finished products to consumers, electronics manufacturers, or other businesses (Capraz et al., 2015). Finally, the last source of revenues concerns the different government subsidies and programs offered to e-waste recycling companies to encourage the recovery and recycling of e-waste (Capraz et al., 2015). In Belgium, there is no subsidy from the state for recyclers, but Recupel does remunerate recyclers with whom they have a contract, as stated above.

Table 2 – Sources of costs (1. -6.) and revenues (7. – 9.) of a WEEE recycling facility

	Inclusion in the model	References
1. Purchasing cost	✗*	Karakayali et al., 2007 ; Capraz et al., 2015
2. Transportation costs	✗	Singh et al., 2022
3. Holding costs	✓	Singh et al., 2022
4. Labour costs	✓	Capraz et al., 2015 ; Cui & Forssberg, 2003
5. Processing costs	✓	Capraz et al., 2015 ; Stuart & Christina, 2003 ; Dalrymple et al., 2007
6. Fixed costs	✓	Capraz et al., 2015
7. Material sale	✓	Capraz et al., 2015 ; Singh et al., 2022 ; Widmer et al., 2005 ; Malekkhouyan et al., 2021
8. Product/component sale	✓	Capraz et al., 2015
9. Subsidies	✗*	Capraz et al., 2015

*We consider that the facility has a contractual agreement with Recupel to recycle and receives compensation to do so. The 'purchasing cost' is therefore rather a recycling revenue.

4.1.4. Assumptions

Here is a list of additional assumptions made when building the model. While these may not always be true to reality, they make the model simpler, allowing us to focus the analysis on the most important and relevant elements. We first group assumptions identical (although sometimes reformulated or adapted) to those in the paper from Capraz et al. (2015). Those explicitly stated by the authors are marked with an '*":

- * All parameters are deterministic and known in advance, including (but not limited to) sales prices and batch composition.
- The recycler is a price-taker, meaning that the quantity processed and sold does not affect prices.
- Similarly to the previous point, any output can be sold at the specified price, meaning that there is always sufficient demand for them.
- The exact composition of proposed batches is known.
- * Waste types (such as 'PC', 'LCD Monitor', 'Printer', etc.) are homogeneous, meaning that we do not consider variability within a waste type. In other words, sales price, processing rate, weight, quality, and composition of each waste type represent an average for that type, such that all products within a category are treated as one standard product.
- Processing rates for testing, shredding and separation are constant across waste types.
- * Equipment is always available, without changeovers, startups, or downtime, and requires no maintenance.

The assumptions below reflect other considerations that had to be made in the context of our model and that were not covered in the previous sections:

- Disassembly stations may only process one type of waste per day, and their processing rate is different for each product type.
- The processing costs of the different stations are not proportional to the quantity of inputs processed, but to the time they are used. Simply put, if a station is used in period r, it incurs its variable cost for that period, otherwise it does not.
- Holding costs in the warehouse depend solely on weight, regardless of the waste type and the degree of processing.

4.2. Mathematical formulation

In this section, we present our MILP model, starting with its sets and indices (3.2.1.), followed by the parameters (3.2.2.) and decision variables (3.2.3.). We then present the objective function (3.2.4.) and the constraints (3.2.5.) along with explanations.

4.2.1. Sets and indices

Main sets

$r, r' \in R$	The set of time periods (days)
$i \in I$	The set of WEEE products
$j \in J$	The set of components and materials derived from the disassembly or shredding of WEEE products
$t \in T$	The set of testing stations
$d \in D$	The set of disassembly stations
$s \in S$	The set of shredding stations
$n \in N$	The set of separation stations

Subsets

$i_h \in I_h \subset I$	The set of WEEE products containing hazardous materials
$i_{nh} \in I_{nh} \subset I$	The set of WEEE products not containing hazardous materials
$j_c \in J_c \subset J$	The set of components derived from the disassembly of WEEE products
$j_m \in J_m \subset J$	The set of materials derived from the disassembly/shredding of WEEE products
$j_r \in J_r \subset J$	The 'Rest' material derived from disassembly and shredding of WEEE products

4.2.2. Parameters

$P1_i; P2_{j_c}; P4_{j_m}$	Sales price of product *i*; component j_c; material j_m (€/kg)
R	Proportion of products that are suitable to be sold for direct reuse
$B_{i,r}$	Quantity of product *i* in the batch in period *r* (kg)
BR_i	Revenue from Recupel for processing product *i* (€/kg)

RD_{i_h}	Processing rate for the disassembly of product i_h (kg/day)
RT; RS; RN	Processing rate of a testing; shredding; separation station (kg/day)
QD_{j,i_h}	Quantity of output *j* obtained from the disassembly of 1kg of product i_h
$QS_{j,i_{nh}}$	Quantity of output *j* obtained from shredding 1kg of product i_{nh}
TC; DC; SC; NC	Processing cost of a testing; disassembly; shredding; separation station if used (€/day)
ET; ED	Number of employees required to operate a testing; disassembly station
EB; EI; EP	Number of employees required to process the reception of a batch; to operate the incinerator; to process sales orders
E	Number of employees available daily without additional costs
EOT	Maximum daily overtime in number of employees
EC	Cost of labour (€/employee/month)
OTC	Cost of overtime (€/employee/day)
FC	Fixed cost of the recycling facility for the considered period (€)
CW	Capacity of the warehouse (kg)
HC	Holding cost in the warehouse (€/kg/day)
IC	Incineration cost (€/kg)
M	Very large number

4.2.3. Variables

Real variables

$x0_{i,r}$	Quantity of product *i* sent from collection to stock0 in period *r* (kg)
$y0_{i,t,r}$	Quantity of product *i* sent from stock0 to testing station *t* in period *r* (kg)
$w0_{i,r}$	Quantity of product *i* in stock0 in period *r* (kg)

$x1_{i,t,r}$	Quantity of product *i* sent from testing station t to stock1 in period *r* (kg)
$y1_{i_h,d,r}$	Quantity of product i_h sent from stock1 to disassembly station *d* in period *r* (kg)
$z1_{i,r}$	Quantity of product *i* sent from stock1 to direct reuse in period *r* (kg)
$u1_{i_{nh},s,r}$	Quantity of product i_{nh} sent from stock1 to shredding station *s* in period *r* (kg)

$w1_{i,r}$	Quantity of product *i* in stock1 in period *r* (kg)

$x2_{j,d,r}$	Quantity of component/material *j* sent from disassembly station *d* to stock2 in period *r* (kg)
$y2_{j_m,s,r}$	Quantity of material j_m sent from stock2 to shredding station *s* in period *r* (kg)
$z2_{j_c,r}$	Quantity of component j_c sent from stock2 to part recovery in period *r* (kg)
$v2_{j_r,r}$	Quantity of rest sent from stock2 to incineration in period *r* (kg)
$w2_{j,r}$	Quantity of component/material *j* in stock2 in period *r* (kg)

$x3_{j,s,r}$	Quantity of material *j* sent from shredding station *s* to stock3 in period *r* (kg)
$y3_{j,n,r}$	Quantity of material *j* sent from stock3 to separation station *n* in period *r* (kg)
$w3_{j,r}$	Quantity of shredded material *j* in stock3 in period *r* (kg)

$x4_{j,n,r}$	Quantity of material *j* sent from separation station *n* to stock4 in period *r* (kg)
$z4_{j_m,r}$	Quantity of material j_m sent from stock4 to material recovery in period *r* (kg)
$v4_{j_r,r}$	Quantity of rest sent from stock4 to incineration in period *r* (kg)
$w4_{j,r}$	Quantity of material *j* in stock4 in period *r* (kg)

o_r	Amount of overtime in period *r* in number of employees

Binary variables

$\alpha_r = 1$	if the proposed batch in period *r* is processed
$\varphi1_{t,r} = 1$	if testing station *t* is open in period *r*
$\varphi2_{i_h,d,r} = 1$	if disassembly station *d* processes product i_h in period *r*
$\varphi3_{s,r} = 1$	if shredding station *s* is open in period *r*
$\varphi4_{n,r} = 1$	if separation station *n* is open in period *r*
$\omega1_r = 1$	if rest material is sent for incineration in period *r*
$\omega2_r = 1$	if products/components/materials are sold in period *r*

4.2.4. Objective function

$$\begin{aligned} maximize \quad & Revenues \\ & -(FixedCosts + OperationalCost \\ & + HoldingCosts + IncinerationCosts + LabourCosts) \end{aligned}$$

s.t.

$$Revenues = \sum_i \sum_r (z1_{i,r} * P1_i) + \sum_{jc} \sum_r (z2_{j_c,r} * P2_{j_c}) + \sum_{j_m} \sum_r (z4_{j_m,r} * P4_{j_m}) + \sum_i \sum_r (B_{i,r} * BR_i * \alpha_r)$$

$$FixedCosts = FC$$

$$OperationalCosts = \sum_t \sum_r (\varphi1_{t,r} * TC) + \sum_{i_h} \sum_d \sum_r (\varphi2_{i_h,d,r} * DC) + \sum_s \sum_r (\varphi3_{s,r} * SC) + \sum_n \sum_r (\varphi4_{n,r} * NC)$$

$$HoldingCosts = \sum_i \sum_r \left(w0_{i,r} + w1_{i,r}\right) * HC + \sum_j \sum_r \left(w2_{j,r} + w3_{j,r} + w4_{j,r}\right) * HC$$

$$IncinerationCosts = \sum_{j_r} \sum_r \left(v2_{j_r,r} + v4_{j_r,r}\right) * IC$$

$$LabourCosts = \sum_r (o_r * OTC) + (E * EC)$$

4.2.5. Constraints

Collection

Constraint (1) ensures that if a batch of WEEE is accepted, it is sent to stock0 in its entirety. Constraints (2) and (3) are flow constraints for stock0, for the first and other periods respectively, ensuring that products entering stock0 are either kept in stock, or sent to a testing station.

$$B_{i,r} * \alpha_r = x0_{i,r} \quad \forall i \in I , r \in R \tag{1}$$

$$x0_{i,r} = w0_{i,r} + \sum_t y0_{i,t,r} \quad \forall i \in I ; r = 1 \tag{2}$$

$$w0_{i,r-1} + x0_{i,r} = w0_{i,r} + \sum_t y0_{i,t,r} \quad \forall i \in I ; r > 1 \tag{3}$$

Testing

Constraint (4) ensures that each product that enters a testing station also leaves it, while constraints (5) and (6) are the flow constraints for stock1. Constraint (7) limits the quantity processed by a testing station to its processing rate and constraint (8) limits the quantity of WEEE that can be sold for direct reuse.

$$y0_{i,t,r} = x1_{i,t,r} \ \ \forall i \ \in I\ , t \in T\ , r\ \in R \tag{4}$$

$$\sum_t x1_{i,t,r} = w1_{i,r} + \sum_d y1_{i_h,d,r} + \sum_s u1_{i_{nh},s,r} + z1_{i,r} \ \ \forall i\ \in I\ ; r = 1 \tag{5}$$

$$w1_{i,r-1} + \sum_t x1_{i,t,r} = w1_{i,r} + \sum_d y1_{i_h,d,r} + \sum_s u1_{i_{nh},s,r} + z1_{i,r} \ \ \forall i \in I\ ; r > 1 \tag{6}$$

$$\sum_i x1_{i,t,r} \leq \varphi 1_{t,r} * RT \ \ \forall t \in T\ , r\ \in R \tag{7}$$

$$\sum_{r=1}^{r\prime} z1_{i,r} \leq \sum_{r=1}^{r\prime} B_{i,r} * R \ \ \forall i\ \in I\ , r'\ \in R \tag{8}$$

Disassembly

Constraint (9) defines the quantity of components output by a disassembly station, by means of a bill of materials. Constraint (10) only allows products to be disassembled in stations manned by an employee. Constraints (11) and (12) are the flow constraints for stock2 and constraint (13) limits the quantity processed by a disassembly station to its processing rate, depending on which product is processed. Finally, constraint (14) ensures that each disassembly station can only process one type of hazardous WEEE per period.

$$\sum_{i_h} y1_{i_h,d,r} * QD_{j,i_h} = x2_{j,d,r} \ \ \forall j\ \in J\ , d \in D, r\ \in R \tag{9}$$

$$y1_{i_h,d,r} \leq \varphi 2_{i_h,d,r} * M \ \forall ih \in Ih, d \in D, r\ \in R \tag{10}$$

$$\sum_d x2_{j,d,r} = w2_{j,r} + \sum_s y2_{j_m,s,r} + v2_{j_r,r} + z2_{j_c,r} \ \ \forall j \in J\ ; r = 1 \tag{11}$$

$$w2_{j,r-1} + \sum_d x2_{j,d,r} = w2_{j,r} + \sum_s y2_{j_m,s,r} + v2_{j_r,r} + z2_{j_c,r} \ \ \forall j \in J\ ; r > 1 \tag{12}$$

$$\sum_j x2_{j,d,r} \leq \sum_{ih} \varphi 2_{i_h,d,r} * RD_{ih} \ \ \forall d \in D, r\ \in R \tag{13}$$

$$\sum_{i_h} \varphi 2_{i_h,d,r} \leq 1 \ \forall d \in D, r\ \in R \tag{14}$$

Shredding

Constraint (15) is the equivalent to (9) for shredding, with materials coming from disassembly, and products from testing (through their respective stocks). Constraints (16) and (17) are the flow constraints for stock3, and constraint (18) is the equivalent to (7) and (13) for shredding.

$$y2_{j_m,s,r} + \sum_{i_{nh}} u1_{i_{nh},s,r} * QS_{j,i_{nh}} = x3_{j,s,r} \;\; \forall j \in J\,, s \in S\,, r \; \in R \qquad (15)$$

$$\sum_{s} x3_{j,s,r} = w3_{j,r} + \sum_{n} y3_{j,n,r} \;\; \forall j \in J\,; r = 1 \qquad (16)$$

$$w3_{j,r-1} + \sum_{s} x3_{j,s,r} = w3_{j,r} + \sum_{n} y3_{j,n,r} \;\; \forall j \in J\,; r > 1 \qquad (17)$$

$$\sum_{j} x3_{j,s,r} \leq \varphi3_{s,r} * RS \;\; \forall s \in S, r \; \in R \qquad (18)$$

Separation

Constraint (19), (20) and (21) are the flow constraints for the separation stations and stock4 and constraint (22) is the equivalent to (7), (13), and (18) for separation.

$$y3_{j,n,r} = x4_{j,n,r} \;\; \forall j \in J\,, n, r \; \in R \qquad (19)$$

$$\sum_{n} x4_{j,n,r} = w4_{j,r} + z4_{j_m,r} + v4_{jr,r} \;\; \forall j \in J\,; r = 1 \qquad (20)$$

$$w4_{j,r-1} + \sum_{n} x4_{j,n,r} = w4_{j,r} + z4_{j_m,r} + v4_{j_r,r} \;\; \forall j \in J\,; r > 1 \qquad (21)$$

$$\sum_{j} x4_{j,n,r} \leq \varphi4_{n,r} * RN \;\; \forall n, r \; \in R \qquad (22)$$

Warehouse

Constraints (23) and (24) dictate that the total amount of products, components and materials stored in the warehouse in each period must be less than the storage capacity of the warehouse (23) and must be zero in the last planning period (24).

$$\sum_{i}\left(w0_{i,r} + w1_{i,r}\right) + \sum_{j}\left(w2_{j,r} + w3_{j,r} + w4_{j.r}\right) \leq CW \;\; \forall r \; \in R \qquad (23)$$

$$\sum_{i}\left(w0_{i,r} + w1_{i,r}\right) + \sum_{j}\left(w2_{j,r} + w3_{j,r} + w4_{j.r}\right) = 0 \;\; r = 20 \qquad (24)$$

Incineration

Constraint (26) is used to identify the periods during which “Rest” material is sent for incineration from disassembly and/or separation stations.

$$\sum_{jr}\left(v2_{jr,r} + v4_{j_r,r}\right) \leq \omega1_r * M \;\; \forall r \; \in R \qquad (26)$$

Sales

Constraint (27) is used to identify the periods during which products, components and/or materials are sold for direct reuse, part recovery or materials recovery.

$$\sum_{i} z1_{i,r} + \sum_{j_c} z2_{j_c,r} + \sum_{j_m} z4_{j_m,r} \leq \omega2_r * M \;\; \forall r \; \in R \qquad (27)$$

Labour

Constraint (28) counts the number of employees used in each period to operate the different processes and activities and limits it to the number of employees available, plus overtime. Constraint (29) limits the available overtime for each period.

$$EB * \alpha_r + \sum_t \varphi 1_{t,r} * ET + \sum_{i_h} \sum_d \varphi 2_{i_h,d,r} * ED + \omega 1_r * EI + \omega 2_r * EP \leq E + o_r \quad \forall r \in R \tag{28}$$

$$o_r \leq EOT \quad \forall r \in R \tag{29}$$

Variable domains

The following constraints ensure the non-negativity of the real variables (30) and the binary behaviour of the binary variables (31).

$$x0_{i,r}, y0_{i,t,r}, w0_{i,r}, x1_{i,t,r}, y1_{i_h,d,r}, z1_{i,r}, u1_{i_{nh},s,r}, w1_{i,r}, x2_{j,d,r}, y2_{j_m,s,r}, z2_{j_c,r}, v2_{j_r,r}, w2_{j,r}, x3_{j,s,r}, y3_{j,n,r}, w3_{j,r}, x4_{j,n,r}, z4_{j_m,r}, v4_{j_r,r}, w4_{j,r}, o_r \geq 0 \quad \forall i \in I, j \in J, t \in T, d \in D, s \in S, n \in N, r \in R \tag{30}$$

$$\alpha_r, \varphi 1_{t,r}, \varphi 2_{i_h,d,r}, \varphi 3_{s,r}, \varphi 4_{n,r}, \omega 1_r, \omega 2_r \in \{0,1\} \quad \forall i \in I, t \in T, d \in D, s \in S, n \in N, r \in R \tag{31}$$

Part 5: Analysis

In this part, we conduct multiple analyses using the MILP model in the optimization software AIMMS.

We start with an analysis of the performance of the model, and its convergence to optimality in section 5.1., justifying our stopping criterium of 600 seconds, and continue with the analysis of the base scenario in section 5.2. We then conduct further analyses in section 5.3.

5.1. Convergence of the results to optimality

To ensure consistency in the results, we allow a maximum run time of 600 seconds. While this does not give the most optimal solutions, that is not the goal we are pursuing as we are rather trying to get a general sense of the dynamics at play. Also, as we are unsure of the exactitude of our data, going into fine details does not make sense. Finally, the run time typically allows the model to find a solution close to optimality and the marginal improvement from longer run times is negligible, as shown in Figure 6.

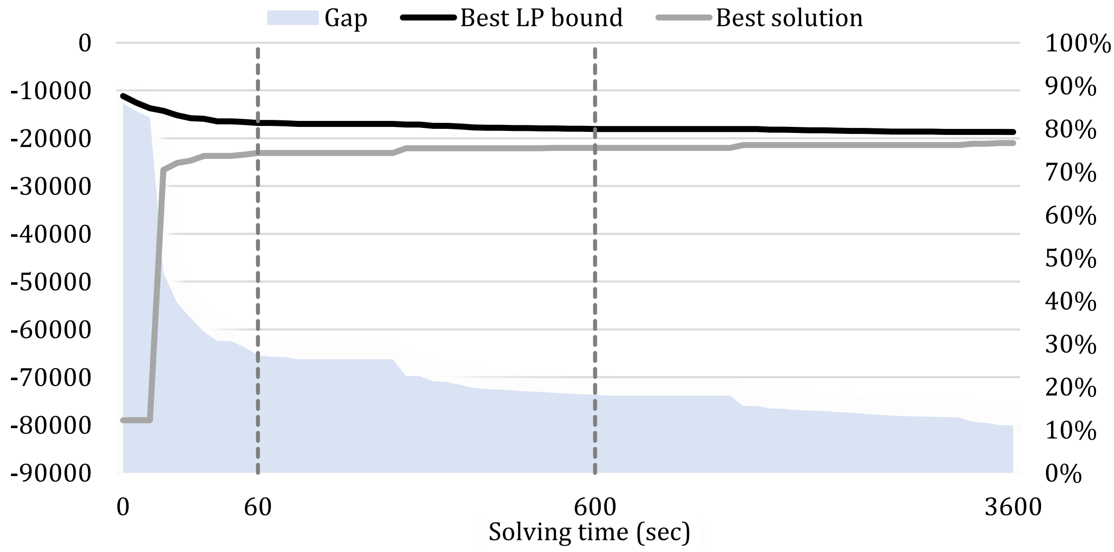

Figure 6 – Convergence of results over time

We can observe three distinct zones representing different convergence phases. In the first zone, which spans from 0 to 60 seconds, we observe significant variation in both the LP bound and solution in 0.08 million iterations. The gap, which measures the difference between the best solution and the best LP bound[3], decreases from 86% to 27%. In the second zone, ranging from the 60th to 600th second, we notice slight changes in the LP bound and solution, halving the gap to 18% after 3.9 million iterations. Finally, in the third zone, from 600 seconds to 3600 seconds, with a total of 30 million iterations, we observe that the results no longer significantly vary, with the gap stabilizing at around 11%

This analysis shows the exponentially diminishing returns of additional iterations and shows that as a compromise between solving time and solution quality, stopping the algorithm at 600 seconds is therefore appropriate.

Following this, we show how the complexity of the model impacts the different optimality indicators through nine cases. The first three cases involve the base scenario with the predefined batch, run over a planning horizon of one week, one month, and three months. The other three cases involve a reduced batch containing only three types of WEEE (‘PC’, ‘LCD Monitor’, and ‘Vacuum cleaner’) over the same planning horizons. The time limit is set at 600 seconds, and the results are found in Table 3.

The first observation is that a longer planning horizon greatly increases complexity, and therefore computational time required to reach optimality, as illustrated by the exponentially increasing number of iterations and solving time in the reduced batch cases.

Table 3 – Computational performance for different model complexities

	Planning horizon	Solving time (sec)	Gap (%)	Iterations	N° of variable	N° of constraints
Full batch	1 week	600	2	34 216 225	3 857	2 728
	1 month	600	18	3 945 001	15 407	10 888
	3 months	600	31	340 720	46 207	32 648
‘PC’, ‘LCD Monitor’ & ‘Vacuum cleaner’	1 week	0.39	1	1 362	3 187	2 328
	1 month	5.92	2	74 905	12 727	9 288
	3 months	600	16	1 181 536	38 167	27 848

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[3] The Linear Programming (LP) bound is an upper bound of the solution obtained by relaxing constraints, for which the program knows that no better solution can be found.

With the full batch cases, we can see that a longer planning horizon, corresponding to a larger problem size, allows fewer iterations to be completed in the limited amount of time, resulting in further-from-optimal solutions. Comparing the 1-week cases gives an idea of the increased complexity caused by increasing the number of product types in a batch from 3 to 13. The full batch case almost reaches optimality within the time limit, in over 34 million iterations, while the reduced batch case requires only 1 362 iterations to reach optimality in under a second.

5.2. Base scenario

The planning horizon covers a period of one month divided into four weeks of five days each. The facility consists of a collection center, a testing station, ten disassembly stations, two shredding stations and one separation station. There are 10 employees available and a maximum overtime of 3 equivalent employees[4]. The batches consist of thirteen product waste types and can be collected on the first day of each week. There are twenty-five types of outputs (components from hazardous waste types and materials from all waste types) recovered from the products after disassembly and/or shredding.

For metallic materials, 'Metals (Fe)' include pure ferrous metals such as metal casings from WEEE; 'Mixed metals (Fe)' include PCBs, fans, motors, and others from bulk recycling operations; and 'Metals (non-Fe)' include alumina, coppers, and others. Concerning plastic materials, 'Plastics' include pure plastics such as plastic casings from WEEE, while 'Mixed plastics' include waste plastics, plastic casings and other plastic contents obtained from bulk recycling operations i.e., shredding and separation (Capraz et al. 2015).

All the data for the parameters used can be found in Appendices 4 to 8.

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[4] As we are working with daily periods, we consider overtime as extra employees such that a day of overtime is equivalent to an extra employee at work, corresponding to 8 hours of overtime.

5.2.1. Preliminary analysis

We first make an analysis on the base model and parameters. In this scenario with 4 identical weekly batches, we get €106 000 of revenues and €127 000 of costs, resulting in a monthly loss of €21 000. The decomposition of revenues and costs can be found in Figure 7.

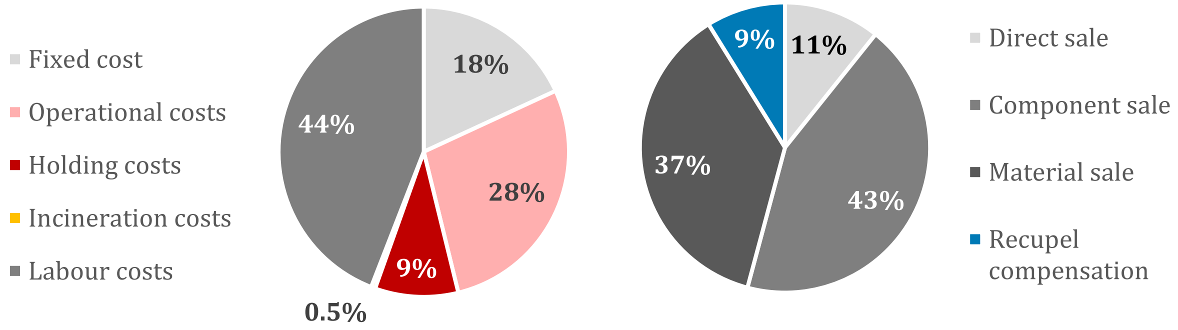

Figure 7 – Decomposition of costs (left) and revenues (right) in the base scenario

As we can see, labour costs account for almost half of all the costs, while incineration costs -defined as the negative 'revenue' from selling rest materials to an external incinerator - are negligible. Component and material sales[5] account for the majority of the revenues, and the Recupel compensation, defined as 50% of the Recupel contribution per product, only yields a meager 9% of the revenues.

With this base scenario, employees are highly utilized (100%), with no overtime. Disassembly stations have an overall utilization of 61%, increased to 98% when only looking at the instances when they are used, which makes sense considering how labour intensive this process is and how expensive labour is. As for the shredding stations, their utilization is at 57%.

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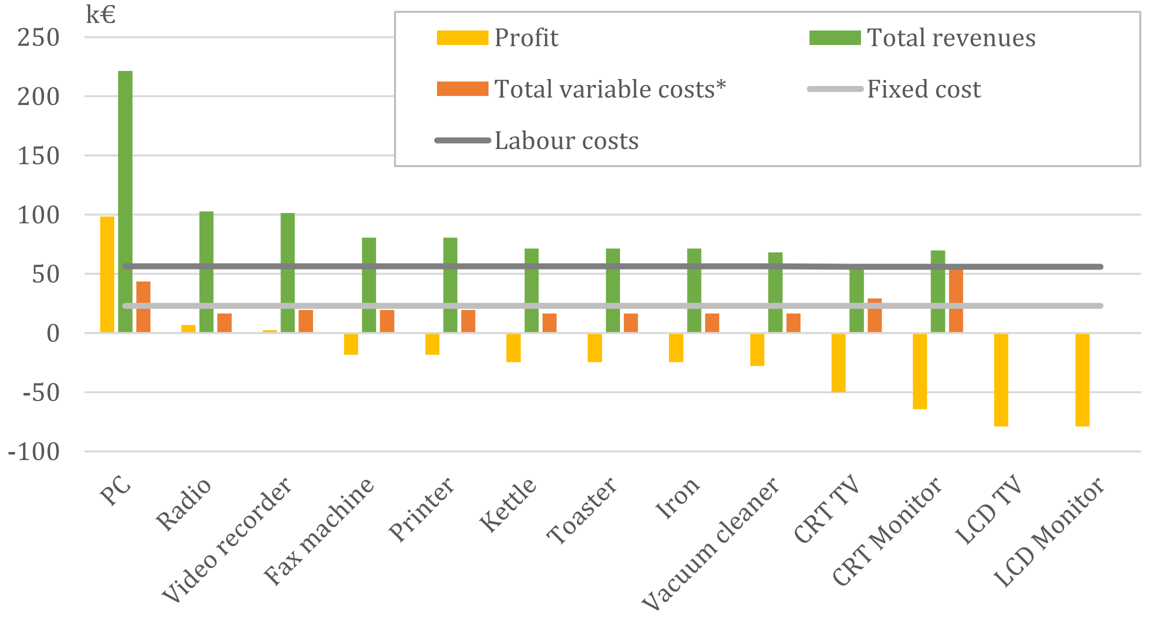
[5] These also include the 'sale' of hazardous components with negative price i.e., for which the facility must pay an authorized company for their proper recovery, destruction, or further processing.

5.2.2. Single product type batches

In this scenario, we run the model with single product batches of the same weight as the base scenario (39.75 tons) to understand more about the profitability of recycling the different products, as well as the utilization of the various stations and employees. Figure 8 shows the results for each product category and Table 4 shows the number of batches processed, giving an indication of the profitability and processing capacity of the facility.



* Variable costs include operational, holding, and incineration costs.

Figure 8 – Profit from batches of a single product type

Table 4 – Number of batches processed in the single product scenario

	PC	LCD TV	LCD Monitor	CRT TV	CRT Monitor	Others
N° of batches	4	0	0	4	4	2

We identify three categories of products, namely (1) WEEE not containing hazardous substances, (2) processed WEEE containing hazardous substances, and (3) unprocessed WEEE containing hazardous substances.

The first category includes ‘Vacuum cleaner’, ‘Iron’, ‘Toaster’, ‘Kettle’, ‘Printer’, ‘Fax’, ‘Video recorder’, and ‘Radio’. These products do not require to be disassembled and are shredded directly after testing. As such, they only yield materials. While the profit is negative (or barely positive for video recorders and radios), it is important to note that the recycling process for this category of products is not labour intensive. In fact, only a small proportion of the available employees are needed to operate their recycling (except at the reception of the batches), meaning that a large part of the labour costs is unnecessary. For all the products in this category, the number of batches processed was two, as shown in table 4, as the facility could not process more due to the limited shredding capacity. With a higher shredding capacity allowing for all batches to be processed, these products would become the most profitable, due to their low processing costs.

All in all, this category of products is profitable and is not labour intensive, but its processing is limited by the shredding capacity.

The second category, processed WEEE containing hazardous substances, includes ‘PC’, ‘CRT TV’ and ‘CRT Monitor’. These products have higher processing costs and are much more labour intensive as they are both disassembled and shredded. However, they also yield high enough revenues to justify their processing thanks to the valuable components and materials that can be recovered, as shown in Figure 9 below.

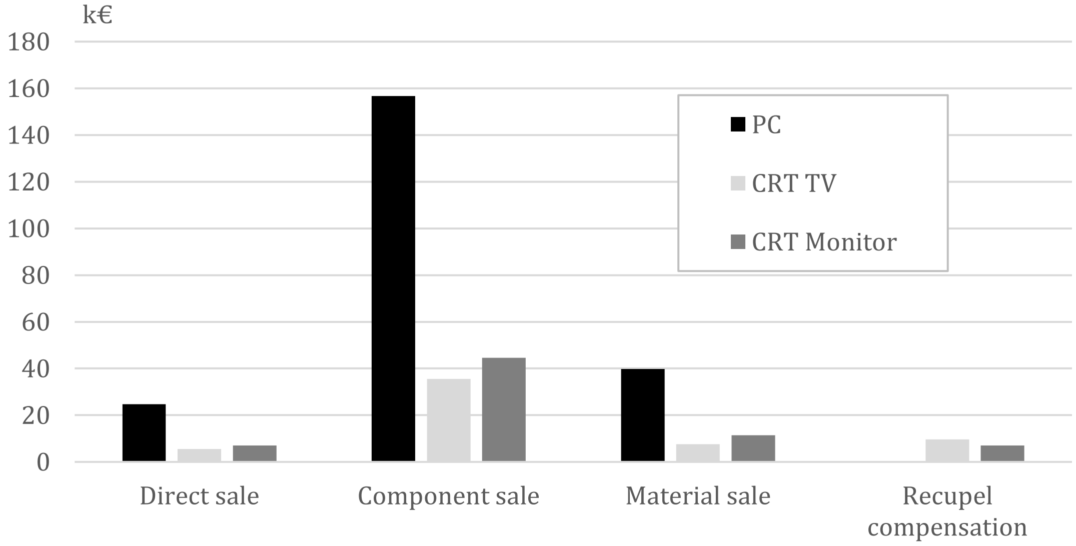


Figure 9 – Revenue decomposition of PCs, CRT TVs, and CRT Monitors in the single product scenario

This category can further be split into two sub-categories: PCs, for which the complete disassembly is crucial given the value of the components that can be recovered, making them the single most profitable product group, and CRT TVs and monitors, which have low revenues due to low material and component values and the costly disposal of the

CRTs, barely outweighing the variable costs. This is reflected in the compensation from Recupel, although its magnitude is too small to make up for the differences.

Finally, the third category, namely unprocessed WEEE containing hazardous substances consists of 'LCD TV' and 'LCD Monitor'. These products are simply not profitable, so if given a choice, they aren't processed, and the facility just incurs the fixed and labour costs.

By reducing the size of the batches to only ten tons to ensure that the processing capacity is not limiting, and by forcing the facility to process one batch, we get the results shown in Figure 10.

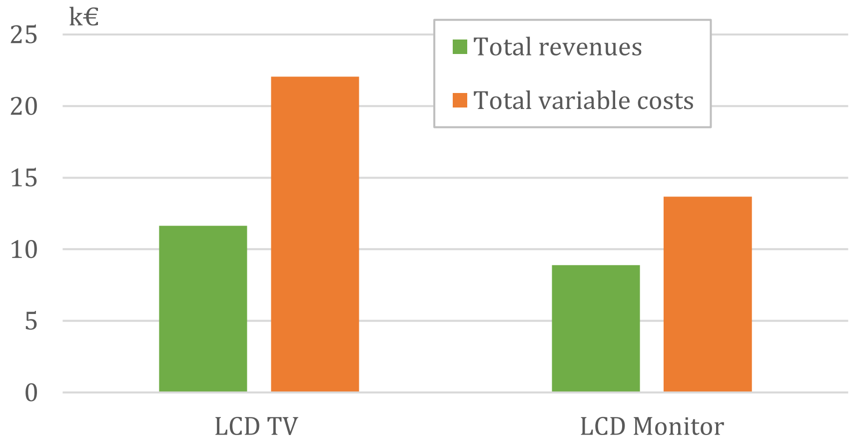


Figure 10 – Variables costs and revenues for a 10-ton batch of unprofitable WEEE types in the single product scenario

Processing products from this third category results in a bigger loss than processing nothing at all. This is mainly due to the very low disassembly rates of LCD devices (see Appendix 6), resulting in high processing and labour costs. It is also important to note that even when given a full month to process a 10-ton batch, one overtime is needed to process the LCD TVs, which have the lowest disassembly rate, with only around 36 products processed per day and station.

Because of this, the marginal loss (not including fixed and labour costs) of recycling 1 ton of LCD TVs is around 1 000€, and around half of that amount for LCD monitors.

These results suggest that the compensation received from Recupel to process LCD products is not sufficient. This could be problematic as it does not incentivize the correct treatment of these WEEE, which contain hazardous substances.

Other options to make LCD TVs and monitors less problematic to process would be to either increase their respective disassembly rates, through staff training or the use of new tools, or to reduce the need for disassembly by only retrieving the hazardous elements and then shredding the rest instead of disassembling completely into components. While this would reduce the revenues from component sales, it could reduce the pressure on disassembly stations, allowing for more products to be processed, and/or for less employees to be needed. Unfortunately, we do not have the necessary data to support the viability of this option.

5.2.3. Maximum batch size

Now that we understand the dynamics at play, we want to determine what the largest possible batch size can be to maximize throughput.

Theoretically, we can calculate it based on the processing rates of disassembly and shredding alone, which are the two limiting processes in the plant. There are ten disassembly stations available, but their processing rates (see Appendix 8) depend on the products disassembled, with very slow (fast) disassembly for LCD (CRT) devices. Therefore, we calculate the maximum throughput while keeping the proportions of the original batch identical.

With this in mind, we determine numerically that the theoretically largest batch, all other things being equal, is 56% larger than the base batch. This results in a utilization of disassembly of 100% (all ten stations used fully at all periods), and of 94% for the shredding stations. As non-hazardous waste types do not need to be disassembled, we can further increase their quantity to 175% of the original batch to reach the shredding capacity.

It is important to note that these results are purely based on processing rates, and do not take any other constraints into account such as labour usage, timing, and the fact that disassembly stations can only process one product type per period.

In fact, determining the maximum batch size with the model yields far different results. For this, we make a few modifications to allow for the batch size to be variable, such that the maximum can be found through the optimization software.

Constraints (1), (8), and (28) and the objective function are modified, and α_r becomes a parameter:

$$\beta * PW_i * \alpha_r = x0_{i,r} \ \ \forall i \ \in I \,, r \ \in R \tag{1}$$

$$\textstyle\sum_{r=1}^{r\prime} z1_{i,r} \leq \sum_{r=1}^{r\prime} \beta * PW_i * \alpha_r * R \ \ \forall i \ \in I \,, r' \ \in R \tag{8}$$

$$EB * \alpha_r + \textstyle\sum_t \varphi 1_{t,r} * ET + \sum_{i_h} \sum_d \varphi 2_{i_h,d,r} * ED + \omega 1_r * EI + \omega 2_r * EP \leq E + o_r \quad \forall r \ \in R \tag{28}$$

$$Revenues = [\ldots] + \textstyle\sum_r \sum_i \alpha_r (\beta * PW_i * \ G_i)$$

With:

β	the size (in tons) of the weekly batch (variable)
PW_i	the proportion of product *i* in a batch (parameter)
$\alpha_r = 1$	on periods when a batch is received, 0 when not (parameter)

Constraint (1) still specifies how much of each product is collected, but only on the periods when a batch is received. The amount of each product received is now the product of its proportion in a batch, and the chosen size of the batch. Constraint (8) is simply rewritten without $B_{i,r}$ which has been removed, such that the quantity of products that can be sold for direct reuse is limited by the quantity collected and the proportion of suitable products. Constraint (28) is modified in the same way. Note that there is no notion of accepting or refusing the batch anymore, as the decision is now to determine the size of the batch, which is why α_r is now a parameter instead of a decision variable. Therefore, all four weekly batches are processed. With these modifications, we can find the optimal batch size by maximizing the profit, and the largest batch size by maximizing β.

The main results for various scenarios are summarized in Table 5 below. With the current configuration, we find that the batch size can be increased by 46%, although an increase of 21% is optimal for profit maximization. This is simply because the limiting resource is always labour, and any increase above 21% results in too much costly overtime. Similarly, removing the possibility of overtime only allows an increase of 17% in batch size. The almost identical results of the optimal base model with and without overtime further illustrate that optimizing labour usage to minimize this category of costs is a priority. The main takeaway here is that the largest profit is made when the labour force is used at its maximum, without (or with very little) overtime.

Table 5 – Maximum and optimal batch sizes

	Objective*	Proportion of base batch	Utilization			Profit (k€)
			Disassembly	Shredding	Labour	
1. Theoretical	Max	156%	100%	94%	-	-
2. Base model	Max	146%	88%	85%	130%	-76
	Optimal	121%	73%	69%	104%	-13
3. No overtime	Max[6]	118%	72%	89%	100%	-53
	Optimal	117%	71%	67%	100%	-14

*'Maximum' maximizes batch size, 'Optimal' maximizes profit

5.2.4. Stock levels and continuity of the planning period

With the way the model is implemented, no final stock is allowed at the end of the planning period of one month. This ensures that everything is processed and sold, especially components and 'Rest' material that are costly to sell. With the single planning period of one month and without the final stock constraint, these items could be kept in stock, as the associated holding cost would be inferior to the loss of properly disposing of these items. Of course, this strategy would not hold if the items kept in stock were carried on to the next month, as they would in reality. Also, starting and ending the month without stock, and conducting analyses on the period is analogous to determining the capacity of a machine on a period that includes the start-up and stopping of said machine.

To take these considerations into account and to come closer to the real, 'continuous' situation of the rolling horizon, we look at a longer planning horizon to see how it impacts the stock levels and other variables, specifically at the monthly transition. For this, we run the model on 12- and 24-week planning horizons. As this greatly increases the number of

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[6] The seemingly odd results when maximizing the batch size result from the fact that the profit is no longer maximized. Shredding is utilized more, and the profit is much worse because products without hazardous substances which could be sold for direct reuse are instead shredded. This would not be the case if the shredding process required a non-zero amount of labour.

variables and constraints, and therefore also the computational intensity, we allow a longer runtime to reach a reasonable solution.

We observe that considering a longer planning horizon does not make a significant difference to the previous results, with profits staying almost the same at around €21 000 loss per month, with longer planning horizons having slightly lower profits due to a greater distance from optimality in the solver.

The stock levels for the 12-week planning horizon are shown in Figure 11. The stocks gradually diminish after the reception of a batch to reach (almost) 0 right before the reception of the next batch, such that increasing the length of the planning horizon does not change the dynamics at hand. This looks a lot like a graph of the level of inventory to minimize costs with the EOQ. In our case, the EOQ is fixed as the weekly batch and the demand is the processing rate of the plant. Again, the irregularities are caused by the software not reaching optimality.

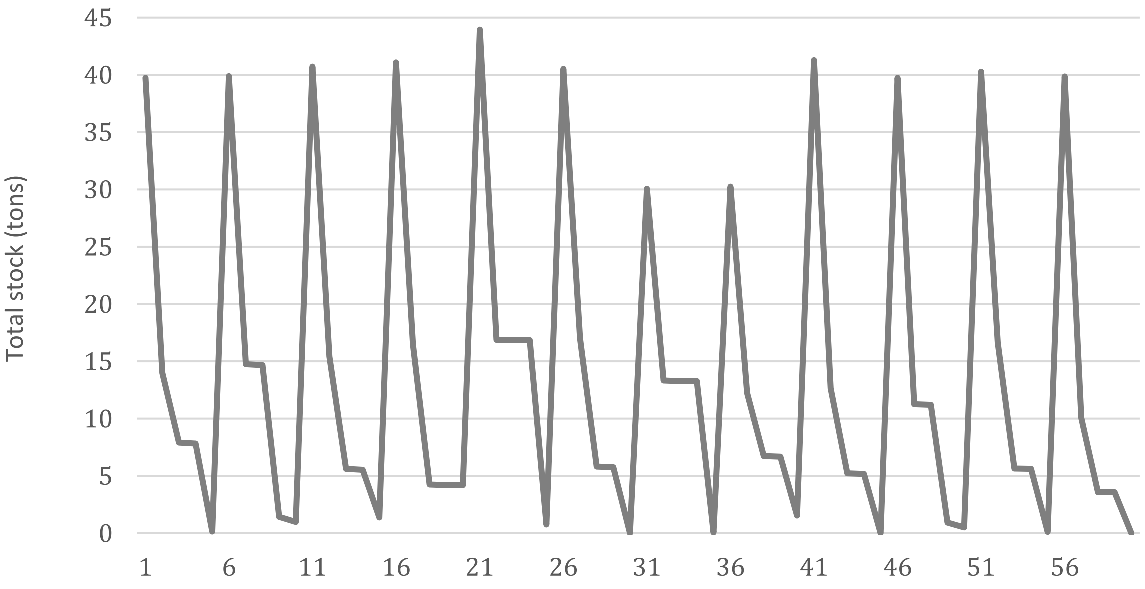


Figure 11 - Total stock levels across a 12-week planning horizon

5.3. Additional analyses on batch characteristics

In this section, we make a few further analyses as examples of what we can achieve using the model, namely modifying batch frequency (5.2.1.), quality (5.2.2.), and composition (5.2.3.).

5.3.1. Batch delivery frequency

In this sub-section, we keep the monthly quantities identical, but change the frequency of batch deliveries, while keeping the intervals regular. The base frequency is weekly, so 4 times per month, and we compare it to frequencies of 1,2, and 8 times per month.

As expected, the revenues stay the same regardless of the frequency of batch deliveries, as they are proportional to the amount processed. The fixed, incineration, and operational costs remain virtually the same. As for the labour costs and holding costs, they vary with the frequency of batch deliveries, as shown in Figure 12.

As batches get larger (with a lower frequency), the holding costs increase, as a large part of the batch must sit idle in the warehouse due to limited processing capacities. The labour costs, on the other hand, only significantly increase when batch deliveries are very frequent, requiring overtime. Also, they do not diminish with lower delivery frequencies as the base scenario does not utilize overtime. However, these two opposite effects do not happen in the same way. Holding costs are far more proportionally sensitive than labour costs, such that higher frequencies are preferred. The optimal frequency seems to be around 4 batches per month. If holding costs were less significant and transport costs were considered, lower delivery frequencies (2 per month) could be preferred.

The increase in labour costs for the lowest frequency is a fallacy in the sense that it is not caused by the delivery frequency in itself, but by the further from optimal solution found for this scenario. With a longer run time, it would most likely reach the same value as for the 2- and 4-batch per month frequencies, with no overtime needed.

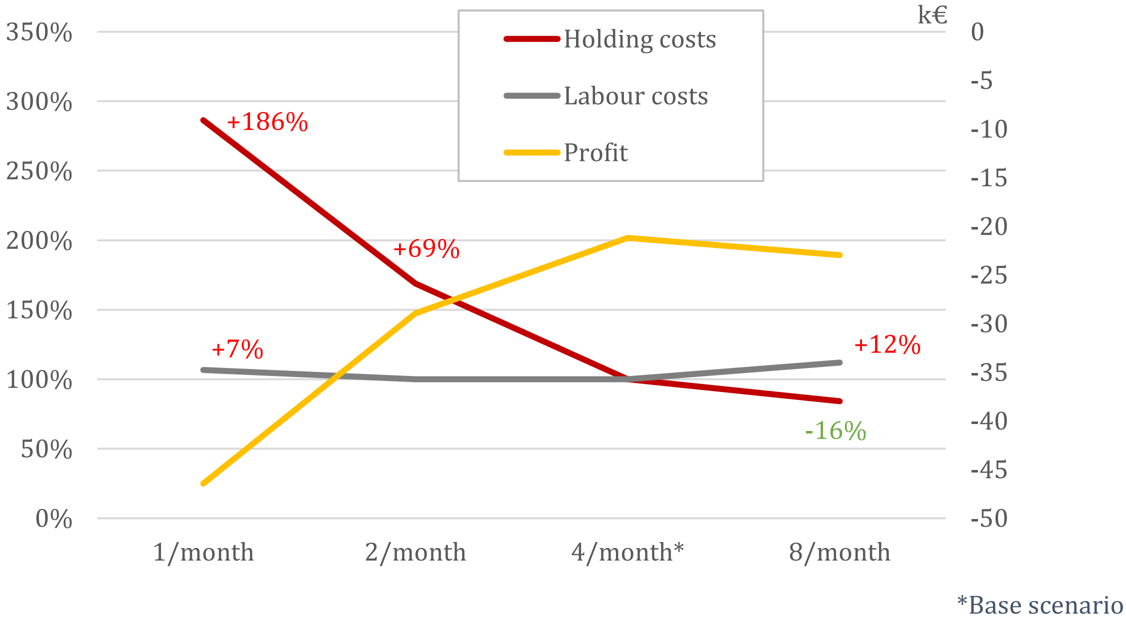


Figure 12 – Impact of batch delivery frequency on holding and labour costs

5.3.2. Batch timing

In this subsection, the responsiveness of the factory in terms of its ability to react to batch delivery delays is tested, given the capabilities of its various stations. To achieve this, starting from the base model, the potential impact on profit of batch delays of one day, two days, and three days during the first week, second week, and combined first and second weeks before the end of the planning period are analysed, when stock levels must be brought to zero. The timeline of the batch deliveries is found in Table 6.

The profit is always more significantly impacted as the duration of the delay increases, particularly when the delay occurs during the week closest to end of the recycling cycle. This is primarily due to an increase in labour costs. However, it is important to note that the factory has responsiveness abilities and can process all the batches in their entirety except in the extreme case where a three-day delay occurs in both weeks.

Table 6 - Timing of batch deliveries

	Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Batch deliveries	Base	X					X					X					X				
	Delayed	X					Y	Y	Y			Z	Z	Z			X				

The delayed cases include deliveries on the two days marked with X, plus one with Y and one with Z.

5.3.3. Batch quality

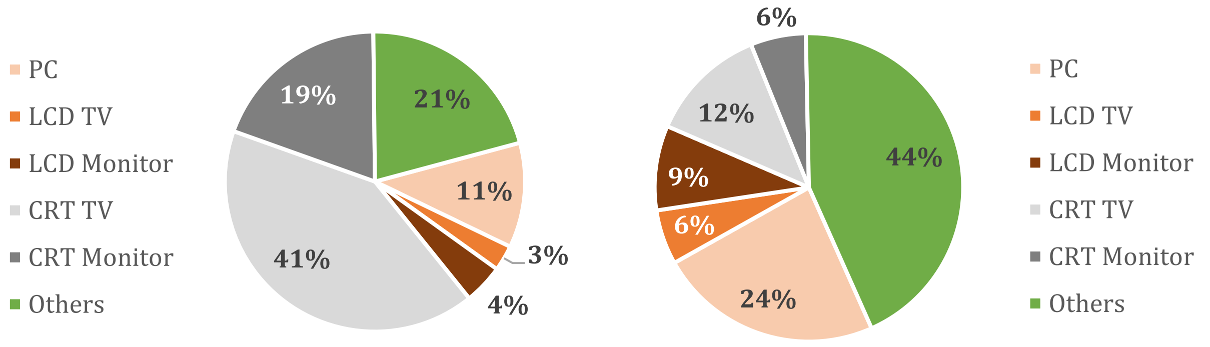
We consider a higher quality to be associated with a higher proportion of products suitable for direct reuse. Because of this, a higher (lower) quality results in a lower (higher) utilisation of processing capacities and available labour. As such, lower than expected quality can be quite impactful as it not only means the products have less value (and must be sold for components and material), but it also increases the amount to be processed at disassembly, shredding, and separation stations which can reduce the size of batches that can be processed and increase operational and labour costs if the facility is already highly utilized. In the base scenario, there is enough extra capacity for this not to happen, even if the quality drops from 5% to 0%. On the other hand, a 1% increase (decrease) in the number of products suitable for direct reuse results in an increase (decrease) in profit of around €2 100 (€1 500).

Our observations regarding the impact of batch quality and quantity on the profitability of the model support the analyses of Özkir et al. (2012) who argue that any change in the quantity of a batch has more effect on profitability than any change in its quality when considering a closed-loop SC network with three processes, namely material recovery, component recovery and product recovery.

5.3.4. Batch composition

We consider a scenario where the product mix of the batch is modified to better reflect current consumption habits in 2023 in Belgium, with a sharp decrease of CRT TVs and monitors (-70%), resulting in a sharp increase of all other categories to conserve a batch size of roughly 40 tons. As CRT devices represented a large share (60%) of the batch due to their heft, the quantity of other products is more than doubled, as shown in Figure 13 below.

With this new composition with 29% less products containing hazardous substances, and over double the amount that don’t, the recycling facility is almost profitable, with a monthly loss of only € 2 000. While the costs increase by 22% due to additional operational costs and the need for overtime, the revenues increase by 45%, mainly thanks



'Others' groups all the non-hazardous waste types

Figure 13 –Batch composition: Base scenario vs. current scenario

to the additional material sales from shredded products. This additional processing is met with an increase in overall utilization of disassembly and shredding stations, at 82% and 93% respectively. Something interesting to note is that full overtime is systematically required on the day of to the reception of a batch and on the following one.

Leveraging the modifications outlined in 5.2.3., we determined that the batch size that maximizes profit in this new scenario is 41.5 tons, for a very slight improvement to a monthly loss of €1 000. This does not result in considerable changes, with more overtime (+3%) and higher utilization of the various stations. However, this does almost bring the shredding stations to their maximum capacity, with a utilization of 97%.

Table 7 - Decomposition of costs and revenues in the base scenario and new scenario

	Base scenario (%)	New scenario (%)	Optimal new scenario (%)
Fixed costs	18	15	14
Operational costs	28	31	31
Holding costs	10	12	12
Labour costs	44	42	43
Direct sale	11	11	11
Component sale	43	35	35
Material sale	37	47	47
Recupel compensation	9	7	7

As we can see in Table 7, the new composition with less hazardous waste generates larger revenues from shredded materials and has a proportionally lower fixed cost due to larger quantities processed.

Part 6: Conclusion

To conclude this work, we start in section 6.1. by summarising its main contributions. We follow in section 6.2. with managerial implications of our results from the analysis, both for recycling plant managers and for the whole (reverse) supply chain. Finally, we outline the limits of the thesis in section 6.3.

6.1. Theoretical contributions

Throughout this thesis, we have explored the topic of the RL of e-waste. We have performed a review of the scientific literature on the different research areas identified, spanning from behavioural science to modelling. Following this, we successfully built a multi-period MILP model as an extension of the one proposed by Capraz et al. (2015) and adapted to the current Belgian WEEE recycling situation.

To model the planning of operations of a recycling facility over time, our main additions were the possibility of stocking products, components, and materials, and the limited labour resources to be allocated between the various labour-intensive processes (batch reception, testing, disassembly, and order preparations) in each period. This model has allowed us to have a more operational aspect of the management of a recycling facility, and to determine the optimal flow of resources, stock levels, utilization of machines and organization of labour.

The main findings can be summarized as follows. Labour is the most critical resource, both in cost and utilization, with overtime sometimes required when batches are delivered to ensure the rapid start of the labour-intensive disassembly process, or in the case of deviations from the optimal plan (for example with late batch deliveries or higher than expected quantities). Additionally, the optimal batch size corresponds to a utilization of labour of 100%, with little to no overtime as labour is extremely expensive in Belgium.

Regarding the model itself, it did not fully run to optimality. The number of product types and the length of the planning horizon increased its complexity, partly due to the large number of possible allocations of the five hazardous product types to the ten disassembly stations in twenty periods. However, this feature is essential given the challenges associated with the disassembly of WEEE, notoriously complex due to the lack of standardization and the presence of hazardous materials, requiring manual labour.

6.2. Managerial implications

WEEE recycling is crucial to minimize environmental and health risks caused by hazardous materials, and to recover valuable and limited material resources. Of course, for WEEE recycling to be undertaken by private actors, it also has to be profitable.

We have found that the profitability is highly dependent on the product mix of processed batches, with very valuable products such as PCs needed to compensate for the costly processing of others such as LCD and CRT devices. The product mix also affects the utilization of the facility, with products containing hazardous substances being labour intensive, while simpler products such as kettles and vacuum cleaners put a larger strain on shredding and separation machines. Therefore, coordination efforts should be made between recycling facilities and WEEE suppliers such as Recupel to ensure optimal use of resources and sufficient profitability.

This coordination and fair allocation of revenues may also be important if high quality products are captured earlier in the supply chain, for example in the wake of new collection or reuse initiatives, as lower quality negatively impacts the profit of the recycler.

Additional mechanisms may be required to increase the profitability (let alone decrease the associated loss) of properly recycling LCD devices to align the objectives of profitability with the best interests of society. This might be achieved through subsidies, research and development efforts to facilitate the disassembly process of these products, legislation for better design for product recovery, or stronger EPR. Alternatively, in a centralized recycling system, tested and sorted products could be sent to facilities specialized in the treatment of specific WEEE types.

The optimal batch size is one that maximizes resource utilization without requiring overtime. With low fixed costs, moderate changes in batch size are not too problematic, although periods of low collection should be anticipated to adapt the number of employees in advance to reduce labour costs. The amount processed should be kept as high as possible (in the limits of the plant's human and physical constraints), especially if the fixed costs are high.

With labour being the most critical resource, the flexibility of employees is crucial, both in terms of possible task allocations and overtime capabilities to ensure the proper functioning of the plant with minimal employees while considering all the possibilities of variability and deviations from the optimal planning.

6.3. Limitations and further research

The primary limitation of this work, as mentioned in the introduction, is the lack of data stemming from a singular source to ground the model in reality. We relied on multiple disparate sources with different economic and historical contexts, which often had to be manipulated, supplemented, and adapted to fit to the model. It would have been very beneficial to extend the analysis through a case study in collaboration with an e-waste recycling facility, which could focus the analysis on a specific problem, with real data.

Specifically, the main source of data came from Capraz et al.'s 2015 case study on a Turkish plant for which the applicability to the current Belgian situation is questionable. Also, the data only spans thirteen product categories - corresponding to the second, third and fourth categories of WEEE listed in the EU WEEE directive- which does not include major categories such as refrigerators and large household appliances and new complex categories such as smartphones, tablets, and laptops. However, it could be argued that the former can be filtered out and recycled by specialized facilities while the latter are often recycled directly by the producers with take-back programs.

Another limitation pertains to the deterministic nature of the model, not only in the data, but also in the possible decisions that can be made for the planning of the recycling facility. Each waste type had a predetermined route to be taken, depending on its composition. However, varying availability of labour, energy prices, and most importantly output prices could justify temporarily modifying the recycling process of certain waste types, as mentioned by Capraz et al. (2015), with varying degrees of disassembly and shredding.

The scope of the analysis is also limited in the sense that we considered the parameters to be exogenous to the optimization, whereas the interaction between decisions from different actors along the (reverse) supply chain cannot be ignored.

Finally, we assumed holding costs to be proportional to weight, but they could depend on volume instead. In that case, the trade-off between the additional sales revenues and holding costs from keeping certain processed materials with low volumes and highly volatile prices in stock to sell them at the most advantageous price could be analysed.

Other extensions of the model in the future could be to consider a longer planning horizon to capture seasonal effects of prices and demand. The fuzzy and stochastic nature of the data could also be included in the model, as WEEE products are extremely diverse in size, composition, quality, age, and complexity.

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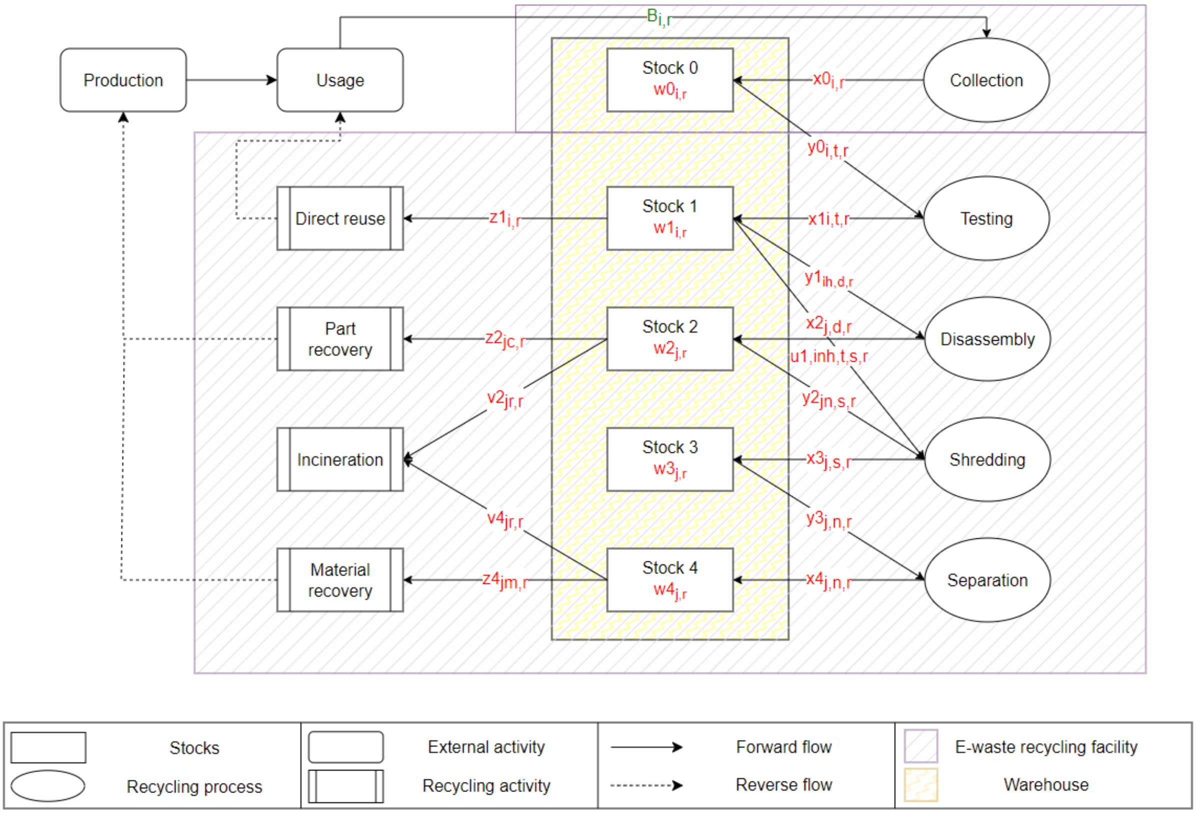
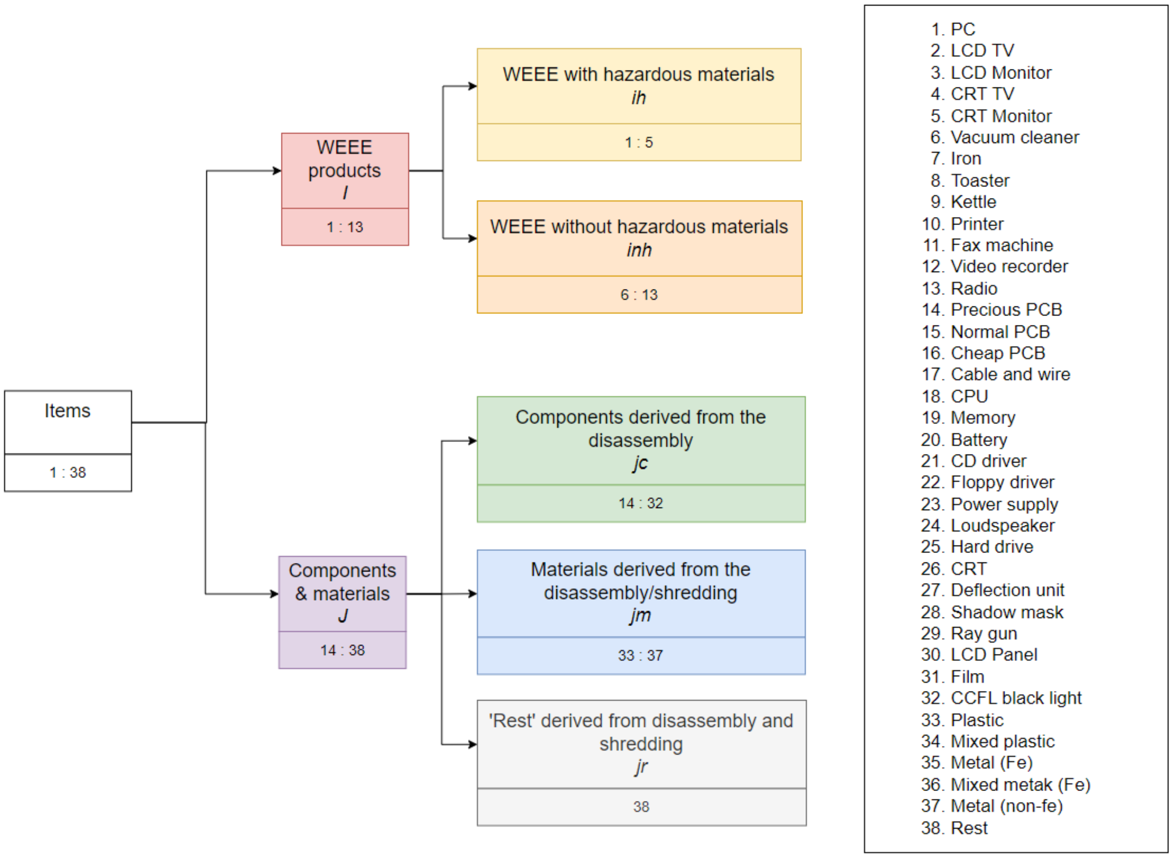
Appendices

Appendix 1 – E-waste recycling facility model: flow and stock variables

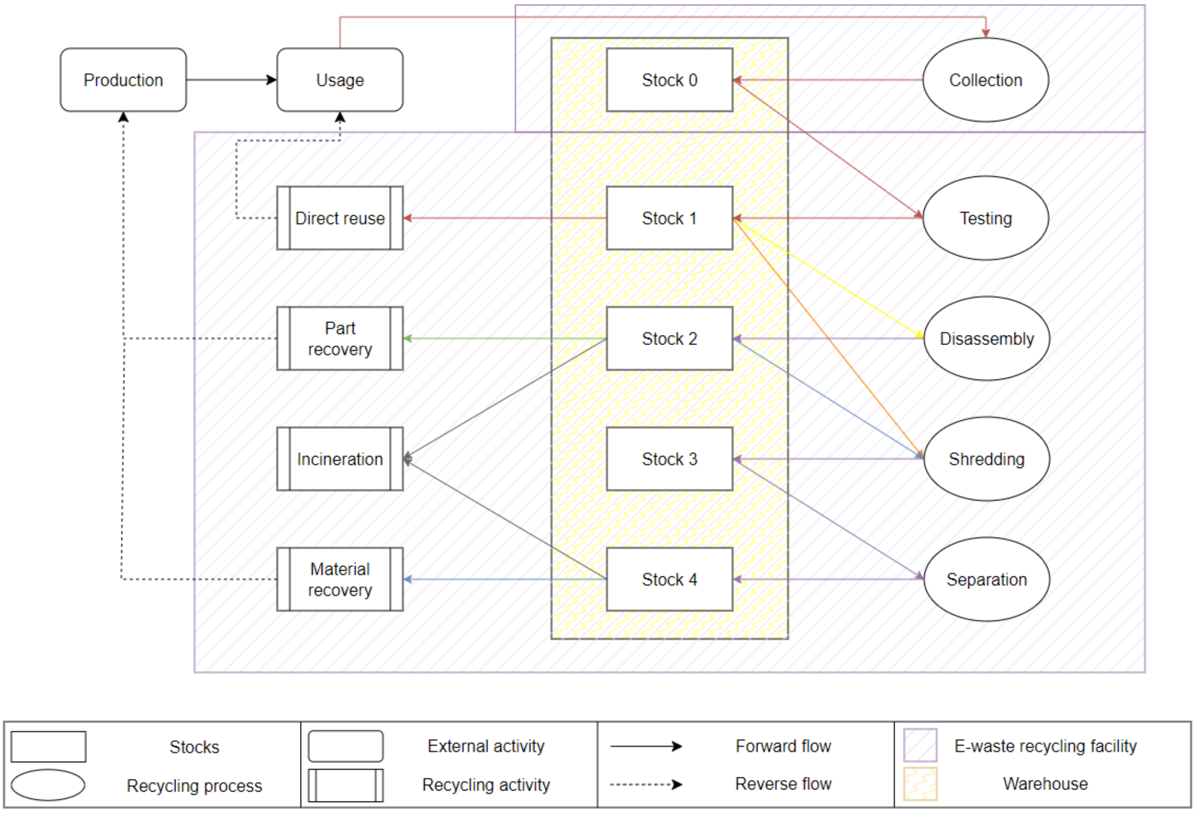


Appendix 2 – E-waste recycling facility model: sets



1. PC
2. LCD TV
3. LCD Monitor
4. CRT TV
5. CRT Monitor
6. Vacuum cleaner
7. Iron
8. Toaster
9. Kettle
10. Printer
11. Fax machine
12. Video recorder
13. Radio
14. Precious PCB
15. Normal PCB
16. Cheap PCB
17. Cable and wire
18. CPU
19. Memory
20. Battery
21. CD driver
22. Floppy driver
23. Power supply
24. Loudspeaker
25. Hard drive
26. CRT
27. Deflection unit
28. Shadow mask
29. Ray gun
30. LCD Panel
31. Film
32. CCFL black light
33. Plastic
34. Mixed plastic
35. Metal (Fe)
36. Mixed metak (Fe)
37. Metal (non-fe)
38. Rest

Appendix 3 – E-waste recycling facility model: product flows (refer to Appendix 2 for color codes)



Appendix 4 – Data on WEEE products ‘i’ (Capraz et al., 2015)

Products ‘i’	Sales price ‘P1$_i$’ (€/kg)[a]	Recupel compensation ‘G$_i$’ (€/kg)[b]	Quantity per batch ‘B$_{i,r}$’ (kg)
PC	3.10	0.0021	4500
LCD TV	1.34	0.4472	1100
LCD Monitor	1.42	0.0970	1700
CRT TV	0.70	0.0603	16 400
CRT Monitor	0.88	0.0438	7 700
Vacuum cleaner	2.20	0.0506	4700
Iron	2.39	0.0207	400
Toaster	2.39	0.0207	500
Kettle	2.39	0.0207	500
Printer	2.63	0.0122	500
Fax machine	2.63	0.0122	150
Video recorder	3.31	0.0243	800
Radio	3.36	0.0620	800

[a] Defined as 3x the price of the components and materials contained in the product

[b] Data from Recupel (2023), defined as 50% of the contribution, and adapted by weight using the average weight for each product type

Appendix 5 – Data on components 'j_c' & 'j_r' (Capraz et al., 2015)

Components 'j_c' & 'j_r'	Sales price '$P2_{j_c}$' (€/kg)[d]	Bill of materials (proportion) 'QD_j'[e]				
		PC	LCD TV	LCD Monitor	CRT TV	CRT Monitor
Precious PCB	5.10	0.0886	0.0108	0.0069		
Normal PCB	1.80		0.0152	0.0387		
Cheap PCB	0.41		0.0498	0.0456	0.0382	0.1128
Cable and wire	1.80	0.0185	0.0152	0.0110	0.0449	0.0567
CPU	36.00	0.0021				
Memory	6.00	0.0041				
Battery	-0.24	0.0051				
CD Driver	0.37	0.0886				
Floppy driver	0.37	0.0381				
Power supply	0.44	0.1359				
Loudspeaker	0.01	0.0041	0.0022	0.0276		
Hard drive	1.62	0.0515			0.0228	
CRT	-0.01				0.6886	0.5087
Deflection unit	1.36				0.0429	0.0493
Shadow mask	0.18				0.0009	0.0486
Ray gun	0.18					0.0019
LCD Panel	0.30		0.1126	0.0760		
Film	0.72		0.0303	0.0152		
CCFL back light	0.12		0.2468	0.1174		
Rest	-2.00[f]	0.0021	0.0020	0.0013	0.0015	0.0013

[d] To account for inflation from 2015 to 2022, we multiplied the values by 1.2

[e] We adapted the quantities to be proportions by weight, and modified the 'Rest' to have exactly 100% weight input to output ratio

[f] This negative 'sales price' represents the cost of incineration for the 'Rest' category

Appendix 6 – Data on materials ‘j_m’ (Capraz et al., 2015)

Materials ‘j_m’	Price ‘$P4_{j_m}$’ [c] (€/kg)	Bill of materials (proportion) ‘QD_j’				
		PC	LCD TV	LCD Monitor	CRT TV	CRT Monitor
Plastic	0.30	0.0350	0.2316	0.2390	0.1500	0.1690
Mixed plastic	0.20					
Metal (Fe)	0.48	0.5263	0.1212	0.3674	0.0102	0.0517
Mixed metal (Fe)	0.66		0.1623	0.0539		
Metal (non-Fe)	4.80					

[c] Prices are adapted from 2015 to current prices by multiplying them by 1.5, following the Producer Price Index (PPI) (OECD, 2023).

Appendix 6 - continued

Materials ‘j_m’& ‘j_r’	Bill of materials (proportion) ‘QS_j’							
	Vacuum cleaner	Iron	Toaster	Kettle	Printer	Fax machine	Video recorder	Radio
Plastic								
Mixed plastic	0.5715	0.6000	0.6000	0.6000	0.2941	0.2941	0.3333	0.3500
Metal (Fe)								
Mixed metal (Fe)	0.3469	0.3000	0.3000	0.3000	0.5882	0.5882	0.4902	0.5000
Metal (non-Fe)	0.0816	0.1000	0.1000	0.1000	0.0980	0.0980	0.1569	0.1500
Rest					0.0197	0.0197	0.0196	

Appendix 8 – Data on processing stations (Capraz et al., 2015)

Stations	Items	Processing rate 'RT, RD$_{i_h}$, RS, RN' (kg/day)	Processing cost 'TC, DC, SC, NC'	Employees required to operate 'ET, ED'[g]
Testing 't'	All	48 000	240	3
Disassembly 'd'	PC	1 864	240	1
	LCD TV	126	240	1
	LCD Monitor	217	240	1
	CRT TV	2 530	240	1
	CRT Monitor	1 184	240	1
Shredding 's'	All	2 800[h]	120	0
Separation 'n'	All	8 120[i]	120	0

[g] Determined based on the processing rate, and the literature on the subject

[h] Data from Shredder and shredders (2023)

[i] Data from Gtek magnet (2023)

Appendix 9 – Other parameters

Parameters		Values	Parameters	Values
Holding cost 'HC' (€/kg/day)		0.05	Maximum labour 'E'	10
Fixed cost 'FC' (€)		23 000[j]	Maximum overtime 'EOT'	3
Warehouse capacity 'CW' (kg)		200 000	Labour cost 'EC' (€/month)	5 600[k]
Proportion of products suitable for direct reuse 'R'		0.05	Overtime cost 'OTC' (€/day)	420[k]
Labour usage	Batch reception 'EB'	5		
	Incineration 'EI'	1		
	Sales 'EP'	3		

[j] Capraz et al., 2015

[k] Statbel (2023): labour cost of 34.9€/hour in the waste management sector, rounded to 35€/hour, and multiplied by 8 (hours/day) x 20 (days/month); overtime is at least 150% of pay, so 52.5€/hour, and 420€/day

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