JOÃO QUARIGUASI FROTA NETO

Eco-efficient Supply Chains for Electrical and Electronic Products

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Eco-efficiënte aanbod ketens voor elektrische en elektronische produkten

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Contents

Chapter 1

Introduction

1.1 Motivation

Since the Industrial Revolution, there are two noticeable changes regarding the way in which we produce goods. The first change is that some of the production processes have become less harmful to the environment. The processed volume of the residuals of manufacturing has been constantly increased throughout the years, in particular within the last century (The Economist [2007a]). Hazardous materials have been phased out (RoHS [2008]). The sources of energy have been altered to decrease environmental footprint (Schipper et al. [1997]). In general, the products themselves have also evolved into more environmentally friendly ones. Products have become less energy hungry. Furthermore, they demand less raw material for manufacturing. Together, these measures have drastically decreased the environmental footprint of products[1].

The second change is that we do it faster and more efficiently[2] than ever done. The rate in which we can transform raw material, energy and labor into goods has particularly risen after the Industrial Revolution (Oxford Advanced Learner's Dictionary, Encarta [2008]). Handcrafting-type production methods have been replaced by the assembly line (Encarta [2008]). Manpower has been partially replaced by the steam engine (Britannica [2008b], Encarta [2008]). Later in this century, workers have been displaced by machines in highly automated factories (Britannica [2008a]).

[1] In this manuscript, we use the term "environmental footprint" as, broadly, the pressure that is exerted on the environment. See definition in section 1.3 of products (at a unit level).

[2] "Efficiency" is a term that is recurrently used throughout this thesis. Unless otherwise stated, we refer to the Oxford dictionary for its definition. **Efficiency**: the quality of doing something well with no waste of time or money.

These changes have lead to a vertiginous productivity increase and, consequently, to an increase in the volume of goods manufactured (Encarta [2008]). Needless to say, the increase in production levels, *ceteris paribus*, increases the pressure we exert on the environment.

On the one hand, therefore, we observe a virtually exponential increase in the number of products we make. On the other hand, we observe a drastic decrease in the environmental footprint caused by each of these products, if compared with their predecessors. The environmental quality balance hangs between the negative effect of the former and the positive effect of the latter. For some relevant indicators of environmental quality, such as greenhouse gas emissions, the gains achieved by cleaner processes have been more than cancelled by the increase in production (Phillipe [2003]).

Furthermore, the pace in which we produce is not likely to slow down in the near future. Business-friendly policies and economic growth of countries such as Brazil, Russia, India and China (BRIC) will bring hundreds of millions to the status of consumers in the near future (O'Neill [2007]). Also, consumers in the developed countries are unlikely to, in a short term, change their consumer habits.

If the velocity in which we consume does not slow down in the near future, it is paramount to find solutions to mitigate, al least, the extra environmental pressure caused by the constant increase in production levels. Even more challenging, in order to keep economic growth, is that it has to be done without jeopardizing present business.

This thesis is motivated by the challenge to cope with the increasing environmental pressure caused by the myriad of goods that make our lives more comfortable and enjoyable. In particular, we focus our efforts on the endeavor to create supply chains that balance the needs of business and the environment.

A bewildering number of products has a significant impact on the environment, and one thesis could not cover them all. We narrow our efforts to the electrical and electronic sector.

Our motivation for this choice is that electrical and electronic products can cause significant environmental impact throughout their entire life cycles. From the raw material extraction to their disposal, electrical and electronic products substantially affect the quality of the environment and human safety (Labouze et al. [2003], Walther and Spengler [2005], WEEE directive [2007], IPP [2007]). They are responsible, for instance, for a substantial percentage of the total carbon we emit (Labouze et al.

[2003]). Electrical and electronic products are also responsible for an increasing percentage of industrial and household waste. It is estimated that 6 million tons of electrical and electronic waste have been generated in Europe alone. Furthermore, it is believed that this number grows at 3% to 5% per year (Braun et al. [2007]). The environmental impact caused by this waste is substantial, due to the number of hazardous material if which such waste in composed (Davis [1998], WEEE directive [2007]).

The rest of this chapter is structured as follows. In Section 1.2, we provide empirical evidence on how consumers, companies, NGOs and governments acknowledge the importance of reducing the environmental footprint of our society. We also cite examples for the particular context of electrical and electronic equipments. In Section 1.3, we present the main definitions used throughout the thesis. In Section 1.4, we define the key terms “sustainable supply chain” and “eco-efficient supply chain”. In Section 1.5, we state the research questions and objectives to this thesis. In Section 1.6, we discuss the methodology used to address our research questions. In Section 1.7, we discuss the structure of the entire thesis. In Section 1.8 we discuss the scientific relevance of the thesis. In Section 1.9 we present the managerial implications of our findings.

1.2 The pursuit for sustainability: empirical evidence

In this section we show examples, from society, of how consumers, companies, governments, and NGOs acknowledge the importance of balancing profit with the environment. We also show evidence for the particular context of electrical and electronic equipments.

Consumers

Nowadays consumers have the potential to alter the way in which goods are produced and disposed. They have the final decision on what to buy, and consequentially on what is going to be produced and how. In developed countries, some consumers have embraced sustainable initiatives. Fair trade food is one of these sustainable initiatives. Despite its disputed benefit for producers in developing countries[3], there

[3] Free market economists advocate that such mechanisms are actually harmful for the farmers, since they prevent the farmer from diversifying into more lucrative crops (Harford [2006])

has never been such an auspicious moment for the movement of fair trade. In 2004 alone, fair trade global sales have reached £100m (Jones [2004]). Furthermore, the label has been growing between 40% to 90% a year since it started in The Netherlands slightly more that ten years ago (Jones [2004]). Many companies, such as Tescos, McDonalds and Starbucks, have incorporated fair trade certified companies among their suppliers (Tesco [2008], Guardian [2007], Guardian [2005a]).

Boycott is another way for consumers to express their preferences or personal values. The 1955 Montgomery Bus boycott started the modern civil rights movement (Friedman [1985]). Gandhi's boycott of British salt and clothes was a historical step towards Indian independency. Boycott is still very much alive in our days. Around 36% of the British boycott one or more brands (Guardian [2005b]). Some consumers boycott Nike and Disney due to, allegedly, bad working conditions (Klein et al. [2004], Guardian [2005b]). Nestlé has suffered boycotts for more than twenty years by campaigners of breast feeding (Klein et al. [2004]). In Great Britain, Nestlé is still the second most boycotted company, and its image is still associated with the promotion of infant formula in developing countries (Guardian [2005b]).

For the particular case of electrical and electronic equipment, however, the signs are conflicting. On the one hand we have examples of products that were way ahead of their times in terms of environmental conservation, and were not particularly successful among consumers. An example is the green PC designed by Siemens in 1993. The computer demanded less than half of the energy of its counterparts during usage, weighted less than half, and could be dismantled in only 4 minutes. Despite being wholeheartedly greeted by environmentalists, sales figures showed to be very disappointing (Podratzky [2005]).

On the other hand, we also see signs of passionate green consumers that are willing to spend their time and money buying *green*. After Greenpeace launched the program: "I love my Mac, I just wish it came in green", thousands of customers have written to Apple computers, demanding more environmentally friendly computers (Greenpeace [2007a]). Millions of Germans return their electronic equipments to their municipalities, without any direct economic return, in order to be recycled and properly disposed (Walther and Spengler [2005]). Consumers have also pressured governments to enact legislation for the proper recycling and disposal of electrical and electronic goods (Pohl [2008]).

Moreover, consumers are also directly engaged in more sustainable supply chains. Some consumers buy carbon credits to offset the footprint of their electronics. They are the ones potentially rationalizing the usage of their household appliances. Furthermore, consumers are in most cases the starters of the reverse channel, either by directly returning their unwanted items (i.e., consumers in Germany for a myriad of electrical and electronic equipments), or handling it via mail (i.e., consumers of Apple's mobiles and MP3 players). They have the choice to simply dispose them into the regular household waste or return them.

NGOs

Non-Governmental Organizations (NGOs) have engaged in a number of ways to protect the environment (Mathews [1997]). They discuss with, confront, and pressure other parts of the society in situations where the environment is at stake. NGOs' relation with companies are both of confrontation and cooperation. Moreover, they have worked as watchdogs, pressing companies to clean their production, and urging governments to sanction and enforce environmental legislation. They have also directly interfered in business, even using disputable and controversial methods, such as sabotaging environmentally unfriendly companies and sectors.

Regarding the cooperation with companies, NGOs have worked on mitigating the environmental impact of firms, for example by working on the design of environmentally friendly procurement (WWF [2008]). NGOs have also partnered with the civil society, by informing and educating consumers (i.e. promoting "Green Labels"), promoting boycotts of environmentally unfriendly brands and products, and facilitating individuals to offset their environmental footprint (i.e. Carbonfund).

Furthermore NGOs have been working as watchdogs for the environment. Greenpeace is the most well-known one. The organization has pressed companies to produce in a more environmentally friendly way, and urged governments to sanction laws enforcing environmental protection. Greenpeace has furthermore denounced illegal logging, toxic waste dumping and usage of toxic chemicals in products (Greenpeace [2006]). In 2005, after being accused by Greenpeace of procuring pulp produced from ancient Finnish forests, Xerox changed its procurement policy (Greenpeace [2007b]). In the new policy, the procured pulp should not have been produced from trees contained in conservation areas and old-growth forests.

There is also numerous evidences on how NGOs have been engaged in reducing the environmental impact of electrical and electronic equipments. Following the intervention of Greenpeace, Dell has recently announced to phase out two key groups of chemicals known to be hazardous to the environment by 2009, i.e. all types of brominated flame retardants (BFRs) and the plastic polyvinyl chlorine (PVC)

(Greenpeace [2007b]). Other computer manufacturers, such as HP, IBM, and Apple, to name some, have also been exposed to such campaigns, with mixed results for the environment. In 2006, Greenpeace launched the campaign “I love my Apple. I just wish it came in green”. The environmental group accused Apple of being irresponsible with the environment. Few weeks after the beginning of the campaign, Steve Jobs made an announcement on the green initiatives of Apple, as well as on the promises to keep the leadership on the green initiatives within the electronic sector (Greenpeace [2007a]). Recently, Sony, Microsoft and Nintendo have also been required to remove all toxic components of their equipment and to improve their take-back programs (GreenPeace [2007]).

NGOs have also helped consumers to choose environmentally friendly products. The “green” labels, for instance, inform consumers about environmental excellence of electrical and electronic products. Green Seal is a example of green label ran by NGOs (GreenSeal [2008]).

Companies

A number of companies have also included environmental protection into their agendas. Take the companies forming the Global Fortune 500, the list of the largest 500 American public corporations as measured by gross revenue. In 2002, 63% of these companies presented some environmental information on their web sites (Rikhardsson et al. [2002]). This number drastically increased in the last years to almost 100%. The drivers for such change are various: to comply with new environmental legislations, to avoid new environmental legislation, to improve green image, to reduce raw material procurement and to save in electricity bills (see Corbett and Kleindorfer [2001] and Kleindorfer et al. [2005]).

It is safe to say that any globally significant corporation has taken some initiatives to reduce its environmental impact. A number of petro-chemical and mining companies, for example, have targeted lower levels of greenhouse emissions. British Petroleum (BP) announced in 1998 that it will reduce its greenhouse emissions in 10% in the year 2010. This target has already been met in 2002 (Kambil and van Heck [2002], Knot [2007]). Companhia Vale do Rio Doce, one of the largest mining companies in the world, recently announced the intention to use a diesel mix containing 20% of bio-diesel in all its locomotives as a measure to mitigate its emissions (Vale [2007]). BHP Billiton will invest US300 million in projects to increase energy efficiency, according to its Climate Change Policy (BHP [2007]).

A number of companies in the electrical and electronic sector have engaged in sustainable activities. They have reduced the number and quantity of hazardous materials in their products and components, and have increased the amount of energy and virgin material reclaimed. They have also increased the amount of waste that is properly disposed. These measures have clearly mitigated some of the undesirable social and environmental effects caused by our consumption of electrical and electronic appliances.

A number of companies in the electric and electronic industries have embraced initiatives to close the loop in their supply chains. IBM, Canon, Xerox, Océ, Kodak and Bosch are ubiquitous brand names in closed-loop supply chains and sustainable supply chains streams of research. These companies are engaged in the re-selling, refurbishing and remanufacturing[4] of used products (Thierry et al. [1995], Fleischmann et al. [1997], Fleischmann [2000], Fleischmann et al. [2003]). More recently, Apple Computers has begun to refurbish its iPods and laptops (Apple [2007a]).

Companies have also partnered with governments to design new environmental legislation. The mobile manufacturer Nokia, for instance, has disclosed very detailed Life Cycle Assessments[5] (LCAs) of its equipments to enhance decision making regarding the new environmental legislation. Nokia has been also actively engaged in the formulation of the new European Integrated Product Policy (IPP) (Singhal [2005]).

Governments

Governments play an important role in the process of environmental protection since the early ages. Over 2,500 years ago, the municipality of Athens prohibited dumping waste within one mile from the gates of the town. In 1408, British king Henry IV declared that waste should be removed from the houses, and that infractors would be fined. In 1890, the British Paper Company was created to make paper and board from recycled materials. In 1956, the Clean Air Act, promulgated in Britain, prohibited the burning of smoking fuels. Legislation these days is focused on the reduction of overall environmental impacts. More recently, according to the Kyoto protocol, 37 of the most industrialized countries are committed to reduce greenhouse gas (GHG) emissions (UNFCCC [2007]).

Concerning the industrial settings, legislations are designed and promulgated with the intention to efficiently mitigate the overall environmental footprint of the product

[4]The terms “refurbishing” and ”remanufacturing” are defined in Section 1.3.

[5]For a definition of LCA see Section 1.3.

or service provided (IPP [2007]). In the last ten years, governments have tightened environmental regulations in the electrical and electronic sector. Among other deliberations, they made Original Equipment Manufacturers (OEMs) and importers fully responsible for the end-of-life of their equipments. The European WEEE directive is the best known example. The directives 2002/95/EC and 2002/96/EC restrict the use of hazardous substances and make the OEMs and importers responsible for the end-of-life of their products (WEEE directive [2007]). In the United States, legislation regarding end-of-use equipments is less restrictive. On the other hand, however, the U.S. government recently promulgated tax incentives to foster activities such as remanufacturing (de Brito et al. [2002], Walther et al. [2007] and Guide [2007]). The tax incentives have helped to create an enormous market for remanufactured products. Americans spend an estimated $ 38 billion on remanufactured products per year (Lund [1998]). A number of other countries have adopted or are planning to adopt European WEEE-alike legislation, including China and some places in the United States. Europe has also promulgated the RoHS directive, phasing out a number of toxic substances from these appliances (RoHS [2008]).

These regulations forced companies to re-structure their supply chains in order to cope with the reverse stream of their products. The next step is the development of a more systemic legislation. The focus swifts from waste minimization to environmental footprint mitigation concerning the entire life cycle of the equipment. Furthermore, it is likely that the next environmental legislations will adopt more market-driven mechanisms, compared to the existing ones. Examples of market-driven mechanisms are the increase in taxes for landfills and tax break incentives for activities such as remanufacturing of electronic products. In Europe studies are being carried out for the implementation of the Integrated Product Policy (IPP [2007]). The objective of the IPP is to

> "(...) reduce the environmental impact from products throughout their life cycle, harnessing, where possible, a market-driven approach in which competitiveness concerns are integrated (Singhal [2005])."

1.3 Definitions

A thesis, as a piece of scientific work, requires unambiguous definitions. These definitions must either come from the existing body of knowledge or must be proposed within the scientific document. For this particular thesis, providing a comprehensive, unambiguous typology is fundamental. The reason is threefold: (i) In Operations Management, the discipline in which this thesis is mainly inserted, literature is known for its contradictory terminologies and meanings (Saunders [1995], Croom et al. [2000]). It is therefore primordial to specify the meaning of the main terms in order to avoid confusion. (ii) This thesis is inherently multi-disciplinary. The fact that this thesis uses terminologies borrowed from different disciplines, and that these terminologies are sometimes overlapping, can cause confusion to the reader. The term "life cycle", regarding a product, for instance, has different connotations in Marketing and Operations Management or Industrial Ecology, as we will explain later in more detail. (iii) The thesis may interest readers with different backgrounds, which might not be familiar with all main concepts used throughout the manuscript.

Two key definitions, however, will not be found in this section. More particularly, the terms "sustainable supply chain" and "eco-efficient supply chain" are important enough to deserve their own sections. The subsequent section will, therefore, be entirely devoted to the definition of these terms.

The following definitions and abbreviations are used throughout the thesis.

Closed-loop supply chain (CLSC): forward and reverse supply chain.

Cumulative Energy Demand (CED): the account for the total gross energy used during the entire life cycle of a product or activity (VDI4600 [1997], Huijbregts et al. [2005]).

Environmental footprint: environmental footprint has two main connotations. The first one means, broadly, the pressure that we exert on the environment. The second is a synonym for ecological footprint, which is a technical term used in the field of Industrial Ecology. The term denotes a particular measure for environmental pressure, as used in Consultancy [2008a].

> "The Ecological Footprint is a resource management tool that measures how much land and water area a human population requires to produce the resources it consumes and to absorb its wastes under prevailing technology." (footprint [2008])

In this thesis, the term denotes the former definition.

E-waste: electrical and electronic waste.

Life cycle: in the disciplines of Operations Management, Operations Research, Reverse Logistics, and Industrial Ecology, the term life cycle refers to the different phases a unit of a device or product goes through, from creation to disposal. These phases include raw material extraction, transportation, manufacturing, usage and disposal. In the fields of Operations Management, it is used in sentences such as "life cycle costing" (Asiedu and Gu [1998]). In environmental studies, it is used in terms such as the aforementioned defined: "life cycle assessment" (Consultancy [2008a]). Conversely, in Marketing, the term "product life cycle" refers to the maturity of the product, and it is related to the type of a product (i.e., The iPod 1GB shuffle, second generation). The life cycle phases in this particular context are growth stage, mature stage, and decline or stability stage (Day [1981]). In this thesis, we do not use the term as currently used in Marketing Research. We use the term as used in Operations Management, and described above.

Life Cycle Assessment. "Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal" (SETAC [2007]).

Network: the term "network" has different connotations within different fields of research, such as Graph Theory, Telecommunication, Sociology, and Operations Management. In the field of Operations Management and Operations Research, the word "network" has two main meanings. In Supply Chain Management, the term refers to the level of analysis used in investigations in supply chain management, i.e. dyadic level, chain level or network level (Croom et al. [2000]). The second meaning refers to the actual physical design of the logistics network, such as the location of manufacturing plants, warehouses, remanufacturing plants and the allocation of flows to these facilities (see Melo et al. [2008]). In this thesis, and in particular in Chapter 3 and Chapter 4, we are interested in physical networks, so the term is used with the latter connotation.

Refurbish: the activity of bringing used products onto a certain pre-defined quality level (Thierry [1997]).

Remanufacture: the activity of bringing used products to the quality level of a new product (Thierry [1997]).

Resell: the activity to sell used equipment in the original used state. Unless stated, no cleaning, testing or updating is performed (Thierry [1997]).

Reuse: re-utilization of equipment by a different owner. Unless explicitly stated, the equipment has not been tested before being sold for the next owner (Thierry [1997]).

Reverse flow: flow of material with opposite direction to the conventional flow of goods. It includes the flow from consumers to second-hand consumers, OEMs, third party remanufacturers, or collectors. (Thierry [1997]).

Reverse supply chain: a supply chain in which the goods travel in an opposite direction to the traditional forward flow. The objective is to reclaim value from these goods and properly dispose them (Thierry et al. [1995]).

Three P's (3P's): *see tripple bottom line (3BL)*

Triple bottom line (3BL): the concept that companies should act in the benefit of their stakeholders. The concept defies the traditional theory of the firm, in which the sole objective of companies is to maximize shareholder wealth (Elkington [1994]). The three bottom lines, also known as goals of sustainability are: people, planet and profit.

WEEE: Waste of Electrical and Electronic Products. The term is applied to the stream of electrical and electronic equipments which is no longer wanted by the original users (WEEE directive [2007]).

WEEE directive: the directive enacted by the European Union, and adopted in many European countries, which makes manufacturers and importers responsible for the entire life cycle of their products (WEEE directive [2007]).

In the next section, we thoroughly define the most important concepts of our thesis, the "Sustainable Supply Chain" and, the "Eco-efficient Supply Chain".

1.4 Scope and definition of sustainable and eco-efficient supply chains

As mentioned earlier in this thesis we focus on the electrical and electronic sector. We intend to contribute to the design of sustainable supply chains for these equipments. In this section we briefly introduce the concepts of sustainable supply chains and eco-efficient supply chains.

1.4.1 Definition of supply chains

The term supply chain, as well as supply chain management, has no universally accepted definition (Croom et al. [2000]). One of the main reasons for such lack of consensus is that the field has been developed within different research disciplines, such as Marketing, Operations Management, Operations Research, and Strategy (Croom et al. [2000]). Tsay et al. [1999] define a supply chain as:

> "A supply chain is two or more parties linked by a flow of goods, information, and funds."(Tsay et al. [1999])

A similar definition is found in Ellram [1990], Lee and Billington [1992] and Christopher [1992] in the context of Supply Chain Management. Conversely, Ballou et al. [2000] define a supply chain based on activities or processes, rather than on the actors involved.

> "The supply chain refers to all those activities associated with the transformation and flow of goods and services, including their attendant information flows, from the sources of raw materials to end users. Management refers to the integration of all these activities, both internal and external to the firm."(Ballou et al. [2000])

In this thesis, we change this definition to include the entire supply chain (i.e. forward and reverse parts), and use the latter definition as the backbone for our definition of "sustainable supply chain". The definition suits our needs since it focuses on activities or processes. We will further elaborate our reasoning in the coming section. We thus obtain the following definition:

> "The supply chain refers to all those activities associated with the transformation and flow of goods and services, including their attendant information flows, from the sources of raw materials to end users, *and from the end-users back to the sources or to disposal.* Management refers to the integration of all these activities, both internal and external to the firm."

1.4.2 Definition of sustainable supply chains

Delineating what is a sustainable supply chain is more difficult than defining what it is *not*. To the best of our knowledge, a universally accepted definition of a sustainable supply chain is, so far, non existent. We posit that the novelty and intrinsic complexity of the term are the causes for the lack of a formal definition. The semantic of the term "Sustainable Supply Chains" indicates longevity: a supply chain that can or will exist forever or for a long time. From the Oxford Advanced Learning Dictionary:

> **sus·tain·able** (...) **2** that can continue or be continued for a long time.

Assuming that companies are profit-oriented and risk-averse, a sustainable supply chain could be thought of as a supply chain that constantly increases the expected value of the firm. This can be achieved by increasing revenues or lowering costs. Under the profit-maximization paradigm, all the other factors such as legislation, consumer response, and labor conditions, are perceived as externalities. Advocating such approach makes the entire field more easily approachable from a structural point of view: all that is needed is to price (and calculate the risk of) such external factors. In other words, a supply chain that, for a long period, generates revenue or lower costs is a sustainable supply chain. In this vein, Reinhardt [1999] provides a macroeconomic explanation of why companies pursue beyond compliance environmental strategies.

Among researchers of closed-loop supply chains, the term "sustainable" is borrowed from the term "sustainable development". The Brundtland Commission, also known as The World Commission for on Environment and Development, defines sustainable development as follows (Brundtland [1997]):

> " (...) sustainable development, which implies meeting the needs of the present without compromising the ability of the future to meet their own (...)"

Kleindorfer et al. [2005] use the term "sustainable" in the context of Operations Management, as to include environmental management, closed-loop supply chains, and a triple-bottom-line (people, planet and profit) thinking into the culture, strategy and operations of companies. The triple-bottom-line concept advocates that the dimensions people, planet and profit are equally important. Companies must orient their efforts not only to profit maximization, but to the improvement of the social welfare and to the protection of the environment. A sustainable supply chain is a supply chain designed with the triple-bottom-line in mind. This definition, although neat and parsimonious, is certainly vague and ambiguous. According to Corbett and

Kleindorfer [2001] and Kleindorfer et al. [2005], the drivers for sustainable operations are purely economic. The term could be perfectly explained by Reinhardt's ideas (Reinhardt [1999]): improvement of corporate image, reduction in virgin material consumption, compliance of environmental regulation are presented as ways to make money. It is, in our opinion, no surprise that the idea that companies act to maximize their profits appeals to those in Operation Management as well. It is unnatural to conceive a supply chain that is not driven by profit. For this reason, we also posit that sustainable supply chains should have profit as a fundamental goal. In our opinion, a good definition acknowledges the growing importance of the triple-bottom-line principle, but remains grounded in the idea of profit-maximizing companies. We define the field of Sustainable Supply Chains as follows:

> "A sustainable supply chain is a supply chain that creates enough economic incentives to be operated, and that has no environmental footprint, and no negative effects on the life of humans."

It is clear from the definition that creating a sustainable supply chain is, nowadays, in most cases not easily attainable. The definition should serve as an aspiration point for operations, i.e., as a normative rather than a descriptive definition.

Furthermore, despite the fact that the environment can support certain levels of pressure (i.e., the carbon emitted will eventually leave our atmosfere; if left alone, farms will eventually become forests again), we avoid using the concept of environmental pressure threshold. The reason for that is twofold. First, because there is no concensus on what is such threshold itself (Schmidheiny [1992]). Second, given that this pressure is predominantely caused by activities outside any given supply chain, using the concept of such threshold makes the definition unpractical from an operational point of view.

As one can infer from the aforementioned definition, a number of elements are related to sustainability of supply chains. It is clear, for instance, that the definition illustrates a pursuit for products and services that respect all stakeholders. The stakeholders include consumers, workers, stockholders, and those directly or indirectly impacted by the company's supply chain. In other words, the aforementioned examples point to supply chains oriented by the triple bottom line: people, planet and profit.

A number of other terms, however, should *not* be confused with sustainable supply chains. Green supply chains and environmentally conscious manufacturing are *not* synonyms for sustainable supply chains. Greening a supply chain means reducing its environmental footprint. Although some researchers argue that greening a supply chain inevitably yields economic benefits (Porter [1991] and Porter and Vanderlinde [1995]), green supply chains are, as currently defined, not fundamentally profit-seeking activities. For the same reason, environmentally conscious manufacturing (ECM) should not be confused with sustainable supply chains. Environmentally conscious manufacturing seeks the production of products in which environmental standards and requirements, accounted during the entire life cycle, are satisfied (Gungor and Gupta [1999]). These two terms should not be mistaken for sustainable supply chains, because they do not include the profit dimension. Reverse logistics and closed-loop supply chains also differ from sustainable supply chains. According to Fleischmann [2000]:

> "Reverse logistics is the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain for the purpose of recovering value and proper disposal."

For closed-loop supply chains, the improvement in the environment is not, or at least not directly, regarded as a goal. Notice that the definition proposed in Fleischmann [2000] does not even mention improvement of the environment. Despite the fact that most reverse and closed-loop supply chains are beneficial for the environment, the objective is to reap the maximum economic benefit from used products (Guide et al. [2003]). Another point worth mentioning is that not every sustainable activity involves returned goods.

1.4.3 Definition of eco-efficient supply chains

The term eco-efficiency has first been proposed in 1992, during the Rio Earth Summit in 1992, by the World Business Council for Sustainable Development (WBCSD). In a few words, eco-efficiency implies "doing more with less" or "creating more value with less impact".

> "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity."(Schmidheiny [1992])

The above definition coined by the WBCSD is possibly the most popular among the general public. Furthermore, it is also used by a number of environmental protection agencies, such as the Australian Environmental Protection Authority, and the U.S. Environmental Protection Agency. The term also permeates sites of public interest, such as Wikipedia and online dictionaries. In line with the WBCSD definition, the Australian Environmental Protection Agency and the Finnish Association for Nature conservation use, respectively, the following definitions of eco-efficiency:

> "In simple terms, eco-efficiency means doing more with less. (...) By being eco-efficient, goods and services can be produced with less energy and fewer raw materials, resulting in less waste, less pollution and less cost." (EPA [2007])

> "Eco-efficiency means increasing the productivity of natural resources. More services and well-being is produced using less raw materials and energy." (FANC [2003])

The term eco-efficiency proposed by the WBCSD is intrinsically linked with the concept of win-win situation advocated in Porter and Vanderlinde [1995]. Porter advocates the idea that companies should invest in the reduction of their environmental footprint, and that this will, by itself, generate positive economic returns. The same rationale would work for governments: tighter environmental legislation would foster innovation for cleaner and cheaper solutions.

This vision has been challenged in Walley and Whitehead [1994], and has generated a vivid discussion that persists to these days. Walley and Whitehead argue that substantial decreases in the environmental footprint of companies are only possible via projects that will have negative or zero returns.

Orsato [2006] argues that the causal relation between mitigation of environmental footprint and returns is moderated by the levels of mitigation. Small improvements can be achieved with no costs, or even with some economic benefits, the so-called "win-win", or "low-hanging fruit" situations (Orsato [2006]). Bigger improvements are more difficult to achieve without extra costs (Orsato [2006])

Corbett and Klassen [2006] argue that the large economic benefits can be obtained via environmental initiatives, but that such benefits are only visible ex post. According to the named "law of the expected unexpected side benefits", environmental excellence causes unexpected improvements in the supply chain. These phenomenon occurs so repeatedly that the unexpected side benefits becomes expected.

A second definition is proposed by the European Environmental Agency (EEA). It defines eco-efficiency based on the concept of sustainable development coined by the Brundtland Commission (Brundtland [1997]):

> "A concept and strategy enabling sufficient delinking of the "use of nature" from economic activity needed to meet human needs (welfare) to allow it to remain within carrying capacities; and to permit equitable access and use of the environment by current and future generations." (EEA [2007]).

This definition of eco-efficiency if as difficult to operationalize as the definition for Sustainable Development proposed by the Brundtland Comission. The main reason for that difficulty lies on the fact that the constructs that define it are, themselves, not properly delineated.

Huppes and Ishikawa [2005] propose a different definition for eco-efficiency based on the concept of Pareto optimality. According to this definition, a process is called eco-efficient if there is no room for decreasing its environmental footprint without increasing its costs or vice-versa. In other words, something (e.g. a supply chain, or a country) is eco-efficient if it belongs to the Pareto efficient production frontier regarding costs and environmental footprint. This definition of eco-efficiency, as a measure of how efficiently we use natural resources, is advocated in Kuosmanen and Kortelainen [2005], Hellweg et al. [2005], Scholz and Wiek [2005] and Kobayashi et al. [2005]. Furthermore, it is used in companies such as Bosch (Otto et al. [2006]) to evaluate different alternatives of products as processes. Figure 1.1 illustrates the frontier.

Akin to the ideas of Huppes and Ishikawa [2005] for eco-efficiency, in this thesis we define an eco-efficient supply chain as:

> "An eco-efficient supply chain is a supply chain which is working on such efficiency levels regarding business and the environment, that it is not possible, with the existing technology, to diminish the total environmental footprint without sacrificing profit."

Notice that, according to our definition, an eco-efficient supply chain is not necessarily a sustainable supply chain. The term eco-efficiency refers to the efficient usage of capital (profit or costs) to reduce the environmental footprint caused by the supply chain. A supply chain that operates with low environmental standards, but

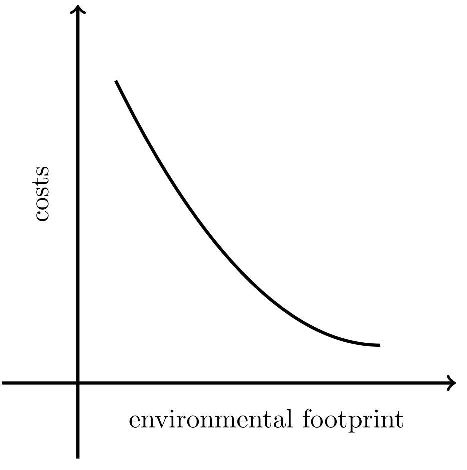

Figure 1.1: Eco-efficient frontier. Adapted from Huppes and Ishikawa [2005]

with very high service levels and low costs can qualify for being eco-efficient. Figure 1.1 illustrates the eco-efficient frontier.

1.5 Research objectives and questions

The main goal of this thesis is to provide guidelines on how to design sustainable and eco-efficient supply chains for electrical and electronic products. This main goal is translated in the following three research objectives.

- Enhance the understanding at the main activities influencing sustainable supply chains (i.e. production, transportation, usage and disposal). More specifically, we propose a framework for the design of sustainable supply chains, based on these factors. We use this framework for the design of sustainable supply chains for electrical and electronic equipments.

- Model and solve the problems arising from the insertion of the environmental dimension in the problems of disposal and remanufacturing. Furthermore, we want to improve the existing methodologies for decision making regarding the preferred solution in such problems. Also, we propose models to allow for the assessment of the trade-offs between costs and environmental variables in designing sustainable supply chains.

- Improve our understanding on marketing issues of sustainable supply chains. We intend to assess which factors may drive the price of second-hand electronics and we test the effect of reference prices for used products.

These objectives are translated into four research questions. We begin the research by identifying the parts of the product life cycle (i.e. raw material extraction, transportation, manufacturing, usage) that impact the environment the most. This translates into the following research question.

RQ1: What are the phases of the life cycle of electrical and electronic products that impact the environment the most?

The second research question deals with the reverse logistics' activities (e.g. reuse, remanufacturing) and how these activities can potentially significantly reduce the environmental footprint of the supply chain:

RQ2: Which activities within the reverse logistics of electronics (i.e. recycling, remanufacturing) can effectively mitigate the environmental footprint of the electrical and electronic supply chain?

The first two research questions are descriptive in nature, and tell us what phases of the life cycle we should focus our efforts on in order to reduce costs and environmental impact. Once it is clear which phases of the life cycle are most important, we study solutions within the scope of these phases that best balance the Decision Maker's preference over costs and environmental footprint. This part of the research is normative. We propose a simple methodology for preference elicitation regarding the measures of environmental footprint and costs, and try to answer the following related research questions:

RQ3: Which multi criteria decision making (MCDM) methods can be used to support decision aid in sustainable supply chains?

Our last research question deals with marketing issues of electronics. We are interested in answering the question of how used, remanufactured and refurbished electronics should be advertised. More specifically, we want to answer which information can be provided to the end consumer to increase its Willingness to Pay (WTP) for used products.

RQ4: Which information could potentially increase the WTP for used remanufactured and refurbished equipment?

1.6 Methodology

This thesis uses different methodologies to answer the different research questions. The use of more than one methodology[6] is, as the name suggest, called multi-methodology or multi-method research. Multi-method research is advocated as a way to triangulate the results in order to increase the validity of the experiment (Campbell [1959], Mingers [2001], Singhala et al. [2008]). The basic premises behind the effectiveness of multi-methods are that different methods have different strengths (see Koppius [2002]). Triangulation has been used in empirical investigations in many different fields, such as Marketing (Dholakia and Simonson [2005]), Information Systems (i.e. Koppius [2002]), Marketing (i.e. Dholakia and Simonson [2005], McAlexander et al. [2002]) and Operations Management (Singhala et al. [2008]).

This thesis uses multi-methods for the reason aforementioned, to solve problems that require different research methods. LCA is the methodology used to answer RQ1 and RQ2. LCA is the most used methodology for the assessment of environmental impact. LCA is recognized in Europe as the methodology for environmental impact assessment, and it is the cornerstone of new environmental legislations, such as the European Integrated Product Policy (The European Comission [2008]).

Multi-objective programming (MOP) and data envelopment analysis (DEA) are used to design and evaluate supply chains (RQ3). MOP is a technique to solve complex problems with conflicting objectives and a high number of possible outcomes (Steuer [1986]). DEA is a non-parametric technique used in Operations Research for efficiency measurement (Charnes et al. [1978]). The rationale to answer RQ3 is to show that these techniques can be successfully applied to the problem of the design of sustainable and eco-efficient supply chains.

In order to answer RQ4 we use a lab experiment. Lab experiments allow for a good establishment of causal relationships, due to the fact that external factors can be perfectly isolated (Friedman and Sunders [1993], Koppius [2002]). Using lab experiments to assess the reservation price or the maximum price a consumer is willing to pay is a common method in marketing research (see e.g., Simonsohn and Ariely [2005] and Krishna et al. [2006]).

[6]We use the term methodology and research method interchangeably (Tashakkori and Teddie [1998], Mingers [2001])

1.7 Structure of the thesis

In broad terms, the objective of this thesis is to improve our understanding on how to create supply chains with the triple-bottom line in mind. We intend to contribute to the stream of research in three directions. Accordingly, the thesis is divided into three parts. In the first part, we determine the main factors influencing sustainability in the reverse supply chains of electrical and electronic equipments. In the second part, we work on the extension of the existing network design models to incorporate the environmental dimension. The third part of the thesis concerns marketing issues in Sustainable Supply Chains. We will now describe each of these parts in more detail.

In the first part of the thesis (Chapter 1 and Chapter 2) we develop a framework for the design of sustainable supply chains. We start by presenting the main players in the electrical and electronic supply chains. Subsequently, we study the environmental impact of the different phases of the life cycle of electrical and electronic equipments.

Furthermore, we show how activities within the reverse flow of materials (reuse, refurbishing and remanufacturing) may significantly mitigate the environmental impact of the life cycle of electrical and electronic products.

In the second part (Chapter 3 and Chapter 4) we study the design of eco-efficient networks. The design of networks[7] (i.e. location, allocation and location-allocation problems) is a well studied problem in the fields of Operations Management and Operations Research. Due to the novelty of the field of sustainable supply chains, however, there are no models incorporating environmental issues into these formulations. More specifically, for this part of the thesis, we model the problem of allocation and end-of-use disposal decisions, as well as decisions regarding remanufacturing. We also propose a measure for the efficiency of supply chains, based on a theoretically optimal frontier. Another important missing part in the literature regards the assessment of the trade-offs between the environmental footprint and costs. Based on that, we develop a simple methodology to improve such assessment. The methodology is also used to help on the decision regarding the preferred eco-efficient network design.

The third part of the thesis (Chapter 5) concerns marketing issues in Sustainable Supply Chains. In other words, we study how properly marketing and channeling returned products can foster the utility of those involved in the supply chain, as well

[7]Unless stated, we use the terms network (or logistic networks) as it is often referred to in the classic logistic literature. A network represents the flows of materials from producers to customers (forward logistics) and the reverse flow (reverse logistics)

as mitigate negative environmental impacts of these supply chains. We focus on the effect that reference prices have on the WTP for used products. The reference prices are the sales price of equipments that are similar to the used ones being advertised.

This thesis is organized so that every chapter of the thesis, with the exception of the introductions and conclusions, refers to a paper published in internationally refereed journals or in the ERIM series. In this way, we make the chapters self-contained, and help the readers interested in a particular chapter or part of the thesis. The specific and relevant literature for each chapter is found within the chapter itself. Chapter 2 presents a framework for the design of sustainable supply chains. Chapters 3 and 4 deal with the design of sustainable supply chains networks. Chapter 5 discusses our findings on marketing issues. Chapter 6 finalizes the thesis with the main results. The structure of the thesis is represented in figure 1.2.

The main ideas in presented in Chapter 1, in particular the motivation and outline for the marketing issue of used and remanufactured part are presented in the following editorial:

> Quariguasi Frota Neto, J. Welcome back my beloved iPod. *Journal of Manufacturing Technology Management*(in print)

In Chapter 2 we develop a framework for the design of sustainable supply chains. We also show that the supply chain of remanufactured electronic products, despite being profit-oriented, is also beneficial for the environment. The findings are based on LCAs of computers and mobiles. This chapter is based on the following paper:

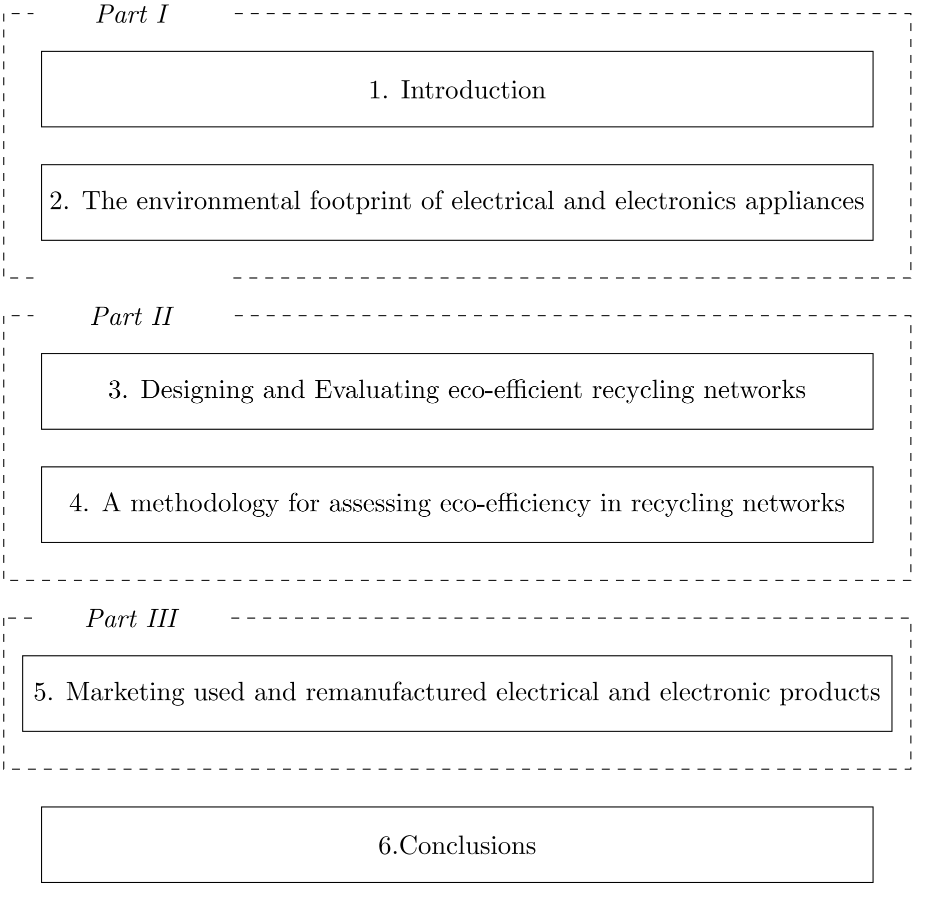

Figure 1.2: Structure of the thesis

Quariguasi Frota Neto, J., Walther, G., Bloemhof, J., van Nunen, J.A.E.E., Spengler, T. (2007) *From Closed-Loop to Sustainable Supply Chains: The WEEE Case.* ERIM Report Series Reference No. ERS-2007-036-LIS, Rotterdam School of Management, Rotterdam, The Netherlands.

In Chapter 3 we propose a model to assess the trade-offs between the environmental impact and costs in the design of a logistic network. We also show how the trade-offs between the aforementioned dimensions can be easily visualized. Furthermore, we propose a measure of efficiency for existing networks of disposable goods. We illustrate our findings with a hypothetical supply chain of used electrical and electronic equipment. This chapter is primarily based on the results of the paper.

Quariguasi Frota Neto, J., Bloemhof, J., van Nunen, J.A.E.E. and van Heck, E.(2008) Designing and evaluating sustainable logistics networks *International Journal of Production Economics*, 111(2):195-208.

In Chapter 4 we develop a simple heuristic to explore the efficient frontier for this problem. The same heuristic enhances the assessment of the trade-offs between costs and the two environmental dimensions: energy and waste[8]. We illustrate the results with the design of a supply chain of used electrical and electronic equipment. This chapter is based on the paper:

Quariguasi Frota Neto, J., Walther, G., Bloemhof, J. , van Nunen, J.A.E.E. and Spengler, T. A methodology for assessing eco-efficiency in logistics networks *European Journal of Operational Research*, In Press, Corrected Proof, Available online since 22 October 2007

In Chapter 5 we study marketing and channeling aspects in sustainable supply chains. In more detail, we explore how information architecture may increase the final value of the remanufactured product. We focus on how External Reference Prices (ERPs) affect WTP for used products.

In Chapter 6 we summarize the results and draw the conclusions.

The appendix contains a glossary with the most important terms used in this thesis and the LCAs performed in this thesis.

[8]For the rest of this document, unless explicitly said, our measure of waste is volume. We are not using toxicity, as we further explain in section 2.5.1

1.8 Scientific contribution

Our contributions to the scientific literature are the following:

- In *Part I* (Chapter 1 and Chapter 2) we contribute to the body of knowledge on sustainable supply chains by assessing the magnitude of the impact that each of the different phases of the life cycle of an electric or electronic product has on the environment. More specifically, we assess the impact caused by transportation, manufacturing, usage and end-of-life of electronic equipments. Furthermore, we show how this information can be used to re-design supply chains to obtain substantial environmental gains. Also, we assess the impact of reuse, refurbishing and remanufacturing, as well as recycling on the environment.

- In *Part II* (Chapter 3 and Chapter 4) we contribute to the field of closed-loop supply chains by proposing the inclusion of environmental measures in the design of recovery networks. The design of recovery networks is a well-known problem, and has been addressed in a number of papers, including Kroon and Vrijens [1995], Ammons et al. [1997], Berger and Debaillie [1997], Spengler et al. [1997], Thierry [1997], Barros et al. [1998], Jayaraman et al. [1999], Krikke et al. [1999], Louwers et al. [1999], Realff et al. [1999], Fleischmann [2000], Shih [2000], Fleischmann et al. [2001], Sodhi and Reimer [2001], Jayaraman et al. [2003], Krikke et al. [2003], Baumgarten et al. [2004], Beamon and Fernandes [2004], de Blanc et al. [2004], Aras et al. [2007], Min et al. [2006b], Min et al. [2006a], Salema et al. [2006], Du and Evans [2007], Ko and Evans [2007], Kaka et al. [2007], Lieckens and Vandaele [2007], Listes [2007], Gomes Salema et al. [2007], Walther et al. [2007] and Srivastava [2008]. Our contributions to the field are the following: (i) We propose an extension of the existing recovery network models in order to incorporate the concept of eco-efficiency. (ii) We conjecture that, even for simple networks, the problem may become computationally untractable for the complete enumeration of the extreme efficient solutions. Our results are based on the general results for multiobjective linear programming[9] (MOLP). (iii) We propose a very simple method to explore the efficient frontier with 3 dimensions. Our method allows for a balanced exploration of the efficient frontier, using a polynomial time algorithm. Furthermore, it allows for the

[9] See Steuer [1986], Sayin [1996], Benson and Saying [1998], Malgorzata and Zhang [1997], Benson [1998], Aurovillian and Wiecek [1998], Steuer [1994], Steuer and Piercy [2005] and Ehrgott and Gandibleaux [2007] for references on the complexity of MOLP

visualization of the trade-offs among the different objectives. Extensive work has been done within the two dimensions, and even ϵ-approximations of the frontier have been proposed (Fruhwirth et al. [1989], Liu et al. [1999], Bernd et al. [2001]). Regarding problems with three objectives, to the best of our knowledge, no ϵ-approximations exists. Furthermore, the complete enumeration of the extreme efficient solutions seems to be computationally intractable, as conjectured.

- In *Part III* (Chapter 5) we contribute to the understanding of the factors affecting the price of used equipments. Despite the fact that second-hand and used and remanufactured products are a multi-million business (Lund [1998]), little research has been carried out regarding the marketing of these products (Guide and Van Wassenhove [2003]). Our contribution lies in examining the effect of reference prices on the final WTP for used products. Previous studies have addressed the problem for a diverse number of reference prices, such as retail price, or minimum bid and reservation price in auctions (Lichtenstein and William [1989], Urbany et al. [1998], Grewal et al. [1998], Kamins et al. [2004], Kamins et al. [2004], Dholakia and Simonson [2005], Ku et al. [2006], Ku et al. [2006] and Lucking-Reiley et al. [2007]). We show evidence that reference prices have a positive effect on WTP for used products. More specifically, we show the effect of the reference price of a new electric and electronic equipment on the WTP of a similar electronic equipment.

1.9 Managerial contribution

The results contained in *Part I* contribute to the managerial practice by mapping the environmental footprint within the life cycle of electrical and electronic products. Furthermore, these results can potentially help decision makers to focus their efforts on the most relevant phases of the life cycle. It also provides a guideline on which reverse logistic activities may significantly reduce the environmental footprint of their products. For the governments within the European Union, the results may provide relevant input for the formulation of the IPP.

In *Part II* we propose a simple methodology for preference elucidation among the many optimal alternatives of eco-efficient recovery networks. The methodology can aid decision makers on deciding the preferable balance between environmental (waste and energy) and business dimensions (costs). In other words, the methodology can potentially help decision makers to find eco-efficient solutions for their supply chains, as well as help them in the elicitation of their preferences regarding the amount of money spent of the environment, and the theoretical trade-offs between these two dimensions.

In *Part III* we study how information, more particularly reference prices, may increase WTP for used equipments. The information that is provided to the consumers of used, refurbished and remanufactured products may increase the final price that these products would reach in auctions, for example. In the CLSC literature, however, little is known regarding the importance of information to the final consumers (Rubio et al. [2006]). The contribution is clear: we show that this particular information is responsible for an increase in customers' average reference prices. This increase will result in higher profit margins for used products.

Chapter 2

The environmental footprint of electrical and electronic appliances

Managing CLSC is a stream of research that has received a lot of attention among academics and society in recent years. As presented in Chapter 1, a number of companies have engaged in closed-loop operations (e.g. BMW, IBM, Canon, Xerox, Océ, Kodak and Bosch). Society, governments and NGOs have been pressing companies to phase out toxic chemicals and to recover and properly treat their end-of-use equipment (Rubio et al. [2006]). Furthermore, literature in the field has flourished in the last ten years. A recent literature review shows that 186 papers have been written in the field in the last ten years (Rubio et al. [2006]).

In CLSC, the objective is to reap maximum economic benefit from end-of-use products (Guide and Van Wassenhove [2003] and Guide et al. [2003]). Some of these benefits are very tangible. These benefits include the profit from the sales of used, refurbished, and remanufactured equipment, and virgin materials. They also include the savings from the reuse of reclaimed spare parts (Thierry et al. [1995]). Other benefits are indirect, and therefore more difficult to evaluate, such as promoting a green image, meeting consumer demand, preparing for further legislation, or preempting legislation (Thierry et al. [1995], Fleischmann et al. [1997], Fleischmann [2000], Corbett and Kleindorfer [2001], Fleischmann et al. [2001], Guide and van Wassenhove [2002], de Brito [2004], Toffel [2004], Kleindorfer et al. [2005]).

Despite the fact that closed-loop supply chains are driven by self-interest of the agents involved (Guide and Van Wassenhove [2003] and Guide et al. [2003]), literature in this field suggests that closing the loop in a supply chain helps to mitigate the undesirable environmental footprint of supply chains (i.e Fleischmann [2000]).The terms closed-loop supply chains and sustainable supply chains are, in some cases, even used interchangeably.

It is expected, however, that the associated level of greenness of sustainable supply chains is moderated by other variables in the supply chain, e.g. product type and end-of-life treatment. In some cases, it is easy to see that closing the loop in a supply chain only changes the type of environmental problem. An anecdotal example is to increase the life of very old refrigerators. This measure decreases the waste stream, but increases the energy consumed. In other cases, however, particularly when the amount of energy used in the production is much larger the energy in the consumption phase, remanufacturing may decrease both the total energy used and the stream of disposed waste.

The solutions in which the business and the environmental objectives are perfectly aligned are called “win-win”, “double-dividend”, “free-lunch” (Orsato [2006]), or “low hanging fruit” solutions (Geyer and Jackson [2004]). In these cases, environmental gains go hand-in-hand with profits. Again, a number of factors will moderate the existence of such situations. The type of the product, its average life-time, the energy consumption profile during its life cycle, and the end-of-life treatment required are some examples of such moderating factors. Furthermore, these solutions differ in terms of their impact: recycling and remanufacturing of different products have different outcomes. In some situations, remanufacturing mitigates a lot of the environmental impact of the life cycle of a product. In others, the effect is marginal or even disputable (i.e., changing one environmental impact for another). In this chapter we look at the impact of existing (and profitable) closed-loop supply chains and intend to determine whether the reverse part of the supply chain significantly and indisputably mitigates the footprint of the product in analysis. Furthermore, we look at the effect of different end-of-use treatments (i.e. reuse, remanufacturing, refurbishing and recycling) on the mitigation of such environmental footprints.

In particular, we analyze the environmental footprint of five electrical and electronic equipments: a computer, a mobile phone, a refrigerator, a washing machine and a TV set. We choose the aforementioned products due to their sheer volume in the category of consumer’s electrical (refrigerator, washing machine and TV set) and electronic (computers and personal mobiles) appliances.

Regarding electronics, we conjecture that mobiles and computers are the best selling electronic equipment in the world. In 2002, computers had reached the mark of one billion units sold worldwide, and for the end of 2008 this figure is expected to grow to 2 billion units (BBC [2002]). In 2006, the number of mobiles in use was estimated at 2 billions worldwide (Singhal [2005]).

Regarding electrical appliances, refrigerators, TV sets, and washing machines are probably the most common appliances in European households. Furthermore, they are responsible for the major part of the energy consumed in European households for the category of electrical equipments (Tukker et al. [2005]).

The difference between electrical and electronics is not easily definable. One possible way to differentiate them regards the way in which the energy works. For electrical appliances, energy is used to physically move something, like a motor. For electronic appliances, the energy is used to transmit information. For this reason, parts such as microprocessors are more abundant in electronics (Britannica [2008c]).

The presence of parts such as microprocessors in electronics may change the energy consumption profile of electronic products, if compared to electrical products. For most electrical equipments, the amount of energy used in manufacturing is much lower than the amount used in the usage phase of the product. Conversely, recent research indicates that for electronics (in particular for computers), manufacturing consumes more energy than usage in the life cycle of the product (Williams and Sasaki [2005]).

Our contribution in this chapter is to analyze whether, based on the latest LCA results for electronics, the energy consumption of electrical and electronic devices is fundamentally different from each other. Furthermore, based on these results, we intend to evaluate the efficacy of reuse, refurbishing and remanufacturing in reducing the environmental footprint caused by these devices.

The results are useful for legislators to set the minimum requirements regarding the levels of reuse, refurbishing, remanufacturing and recycling. The results can also be used by OEMs to focus their efforts on the life cycle phases that can more effectively mitigate the environmental footprint of their products.

We use secondary data from previous studies to validatee our hypotheses. The objective is to cross-check different results and to draw general conclusions regarding the environmental benefits from closing the loop in a supply chain. Our results are particularly interesting for computers and mobiles, since the results for those are limited if compared to the results for electrical devices (Thollier and Jansen [2007]).

This chapter is organized as follows. In Section 2.1 we briefly describe a general supply chain for electrical and electronic products, including the main activities and environmental footprints of the activities encompassed within the supply chain. In Section 2.2 we present the research questions concerning this chapter. These research questions have been previously introduced in chapter 1. Furthermore, we present the main hypotheses for each of the research questions. In Section 2.3 we present the methodology we use to answer the proposed research questions. In Section 2.4 we detail the main principles used to conduct our data collection. In Section 2.5 we analyze the data and try to find common denominators among the results. In Section 2.6 we analyze the results from the previous chapter in order to answer RQ1 and RQ2. In Section 2.7 we discuss the main implications of our findings.

2.1 Characterization of a supply chain for electrical and electronic products

A number of activities within the life cycle of electrical and electronic products have impact on the environment. The main ones are: manufacturing, transportation, usage and end-of-life. In this chapter, manufacturing refers to all activities related to the final manufacturing of the product. It includes raw material extraction, manufacturing of components and final assembly. The transportation phase includes all transportation related to the entire life cycle of the product. It encompasses, therefore, the transportation of raw material, components, products from manufacturers to retailers and consumers, and from consumers to end-of-life. It also includes the transportation of the reverse part of the supply chain (i.e., the transportation of the used product back to the supply chain). Usage, as the name implies, refers to the usage of the product by the consumer. Figure 2.1 illustrates the many phases of a life cycle of a product. The nodes indicate the activities concerning manufacturing, usage and end-of-life. The arcs indicate transportation. A more detailed description of a closed-loop supply chain can be found in Thierry et al. [1995] and Thierry [1997].

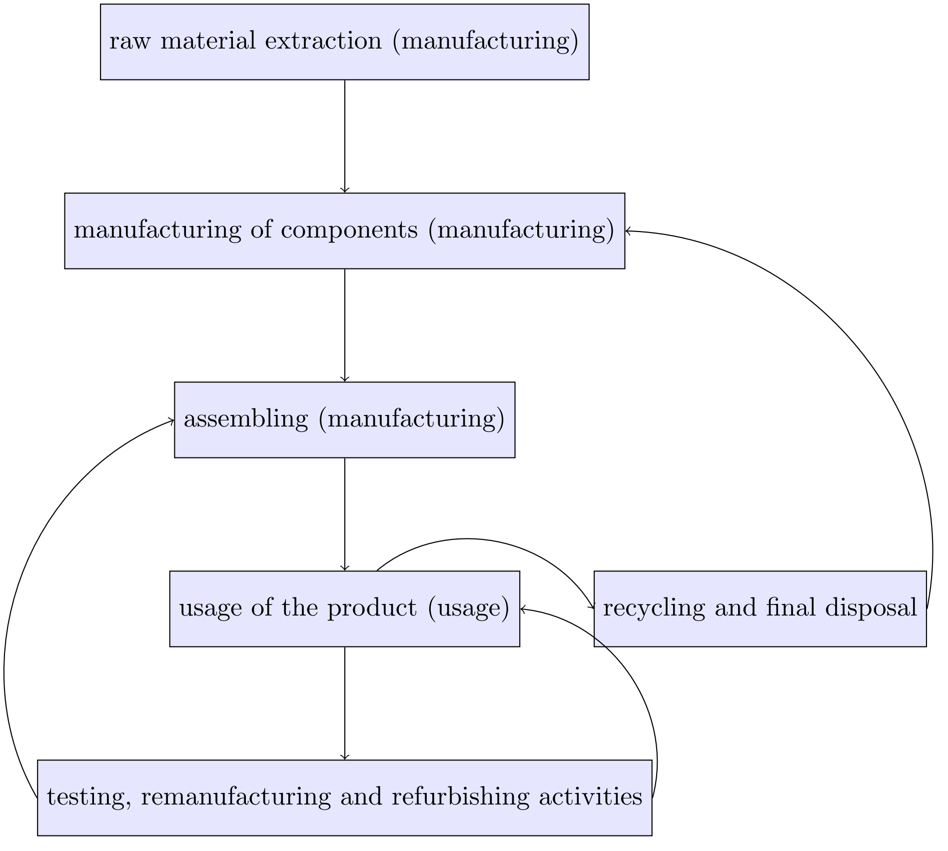

Figure 2.1: Characterization of a supply chain for electrical and electronic products

2.2 Research questions and hypotheses

As discussed in Chapter 1, our research questions are the following:

> RQ1: What are the phases of the life cycle of electrical and electronic products that impact the environment the most?

> RQ2: Which activities within the reverse logistics of electronics (e.g., recycling, remanufacturing) can effectively mitigate the environmental footprint of the electrical and electronic supply chain?

As we further explain in section 2.3, we use CED and waste as indicators for environmental footprint. Research question RQ1 is translated into the following hypothesis regarding computers and mobiles:

> H1.1: For computers and mobiles, raw material extraction and manufacturing are the phases in the life cycle that consume more energy. Usage is second, and transportation is the phase that is least energy intensive.

The hypothesis for electrical appliances is the following:

> H1.2: For refrigerators, washing machines and TV sets usage is the phase in the life cycle that consumes more energy. Raw material extraction and manufacturing are second, and transportation is the phase that is least energy intensive.

H1.1 and H1.2. are formulated differently to reflect the fact that the energy consumption profile for these two classes of devices are expected to be also different.

We only consider the waste generated by the end-of-life product, not the waste generated by the aforementioned phases.

Research question RQ2 concerns the effective activities, embedded in a reverse supply chain, to potentially diminish the energy consumption of the electrical and electronic appliances. RQ2 is translated into the following research hypotheses.

> H2.1: For computers and mobile phones, reuse, refurbishing and remanufacturing substantially diminish the energy used in the life cycle of the product.

H2.2: For computers and mobile phones, reuse, refurbishing and remanufacturing substantially diminish the waste stream in the life cycle of the product.

Regarding electrical equipments:

H2.3: For refrigerators, washing machines and TV sets reuse, refurbishing and remanufacturing do not substantially diminish the energy used in the life cycle of the product.

H2.4: For refrigerators, washing machines and TV sets reuse, refurbishing and remanufacturing substantially diminish the waste stream in the life cycle of the product.

2.3 Methodology

In order to answer these questions we use the LCA methodology. LCA is the assessment of the environmental impact of a product (or service) throughout its lifespan. As a matter of fact, LCA is the most often used assessment tool concerning environmental impacts. The Society of Environmental Toxicology and Chemistry (SETAC) defines LCA as:

> "Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling, and final disposal." (SETAC [2007])

A number of OEMs utilize LCAs to prioritize the investments aiming the reduction of their negative environmental impact. In a questionnaire applied in Switzerland, Germany, Italy and Sweden, 50% of the companies claim to use LCA for decision making (Frankl and Rubik [1999]). Nokia, Apple computers (Apple [2007b]), Canon

(Canon [2007]), Bosch Siemens (WEEEman [2007]) are examples in the electrical and electronic business. Nokia's executive vice president, Olli-Pekka Kallasvuo, reports that (LCA Center [2007]):

> "(...) continuously we use the life cycle thinking to improve our environmental performance. The life cycle thinking covers all environmental and significant impacts in the life cycle of a product and thus constitutes the basis for all environmental activities at Nokia as well as a framework for actions. Based on this approach we set a number of targets for further improvement of our environmental performance."

LCA is also widely used by governments, particularly n the design of legislations concerning the environment. The new European IPP directive, for instance, is based on the LCAs of the most used electrical and electronic appliances (Tukker et al. [2005]). The European Environmental Agency (EEA) also advocates the usage of LCA as a tool for decision making to incorporate environmental dimensions in the production processes (EEA [2007b]). Furthermore, eco-labels also use LCA as the tool to determine the criteria for environmental friendness (Ecoflower [2007]).

In order to make those estimates meaningful we compare them with the total environmental footprint of the complete life cycle of the product. We analyze five items covered by the European Directive on Waste of Electrical and Electronic Equipment, namely a personal computer, a mobile phone, a refrigerator, a TV set and a washing machine. As mentioned in the previous section, the reason to select these items is that we conjecture they are the most popular items for consumer electrical and electronic equipments.

2.3.1 LCA Screening

LCAs have different levels of depth concerning the degree of detail in which the activities and processes are analyzed (LCA Center [2007]). The "screening" is a LCA in which the level of detail allows an assessment of the magnitude of each of the activities, products or services. A screening is defined as:

> "LCA is a model of the complex real world. This means you must limit your model in an intelligent and consistent way. Any study starts with a clear description of the objectives and the scope, as well as a quick screening. This screening shows you what the important issues are, and what are the less important ones."(Consultancy [2008a])

As the research question we address regards the order of magnitude of the different activities in the supply chain, a screening is the right LCA method to use in our analysis.

Once we have defined the type of LCA to be performed, the next step is to define the methodology used for data collection. The subsequent section discuss the methodology used to collect the data used in the LCA.

2.3.2 Functional unit and environmental impact assessment

Life cycle assessment reports emissions for a given functional unit (e.g. year of mobile phone usage). In our study, we consider as a functional unit the total life cycle of a given product. For computers, for instance, our functional unit is the usage of a computer over its entire life cycle. Using such metric helps us to compare the environmental footprint of products with different life cycles. Evaluating the environmental footprint of a product in a time basis is a common approach for electrical and electronic products (i.e., Williams and Sasaki [2005], Choi et al. [2006])

The measures we choose for the assessment of environmental impact are the CED and waste. Recent studies show a high correlation between CED and the Eco-indicator 99 aggregated result [1]. The result is also quite robust for the disaggregated environmental impact indicators, i.e. resource depletion, marine toxicity, etc. (Helias and Haes [2006]). Walk et al. [2005] find an overall Spearman correlation of $\rho^2 = 0.94$ between the CED and the aggregated Eco-indicator results, as well as individual impact correlations ranging from $\rho^2 = 0.73$ to $\rho^2 = 0.96$. It means, in a few words, that CED is a good broad indicator, as suggested in Helias and Haes [2006]. The other indicator we use is waste. More specifically, we look at the waste generated by the end-of-use of the equipment. The reason for choosing waste as a second indicator is twofold: (i) waste is the focus of the current European WEEE legislation (Walther and Spengler [2005]) and (ii) research regarding broad indicators suggests that waste and CED are not highly correlated (Huppes and Ishikawa [2005]).

2.4 Data collection and sources

There are a number of ways to collect data for an LCA (Consultancy [2008b]). Potential sources of data include: "Measurements, interviews, literature search, theoretical

[1] The Eco-indicator 99 is a widely used impact assessment method for LCA. The aggregated results is a measure, based on the weighted mean of the many environmental impact dimensions that comprise the indicator

calculations, database search, and qualified guessing" (Consultancy [2008b]). In our analysis, we use literature search and database search as the main sources of data. The reasons for such approach is twofold. The first reason regards feasibility. For the scope of the thesis, it would be impossible, for instance, to measure the energy used in the production of the electrical and electronic components. A thorough LCA of one of these equipments, in particular, an electronic one would be material enough for a complete Ph.D. thesis (see e.g. Scharnhorst [2005] for mobile telecommunication). The second is the level of detail of the LCA. For *screenings* literature and database search suffice, since the objective is to provide an overview of the main activities regarding the environmental footprint of a given product.

For transportation, we estimate the CED in two ways. First, if available, we extract the data directly from the literature. In some cases, the life cycle information found in the literature already includes transportation. Second, if the data for the environmental footprint of transportation are not available, we estimate them. Our estimations are based on estimations for the distance traveled by the equipment, and on the ratios between distance traveled and energy consumption found in BUWAL (http://www.admin.ch/buwal [2007]).

Regarding energy consumption of usage and manufacturing we use the data found in the literature. The usage of databases here is not suitable due to the high energy consumed by the manufacturing of some very specific components of the electrical and electronic equipments, and in particular for electronic equipments. These specific parts, such as microprocessors for instance, are not well detailed in general databases, such as the BUWAL-250. A result using only the primary materials (i.e. plastic, steel) would distort the results, since most of the energy in the production phase goes into these parts (Scharnhorst [2005], Williams and Sasaki [2005]).

The data itself used in this section has been obtained from LCAs contained in scientific papers, websites and white reports of OEMs, and information in the database BUWAL-250. A detailed description of the data can be found in the appendix. The LCAs used as the source of the data for this chapter had to meet the following criteria:

- The LCA has been published in a book edited by a trustful institution (i.e., the United Nations' University), in a report from a major OEM (i.e. Dell, Apple), in a paper or presentation in a respectable journal or conference in the field of Industrial Ecology (e.g. *Journal of Industrial Ecology*), in a report by a major consultancy company in the field of LCA, or in a master dissertation or a Ph.D. thesis from respected institutions.

- The LCA should contain the total energy demand used in the process or the amount of fossil fuel used.

2.5 Data analysis

In this section we describe the data regarding the energy usage during the life cycle of the products we analyze.

2.5.1 Environmental impact of electronic products

Personal Computers

Computers have become common appliances in households of developed nations. The volume of personal computers sold in the world has grown from thousands, in the beginning of the eighties, to more than a hundred million units in 2002 (Matthews and Matthews [2005]). Furthermore, their life cycle span has drastically diminished during the last twenty years, causing large amounts of computer waste all over the world. Next to the traditional environmental pressure categories, such as acidification and eutrophication, end-of-use computers, if not properly treated, may cause serious threats to human health [2]. In this section we analyze the CED and waste only, so the toxic substances found in a personal computer are not included in the analysis. We assume that such substances **have** to be properly removed. The decision on whether or at which level to remove and threat this substances, therefore, are not addressed in this chapter.

Comprehensive results on environmental impact of computers are scarce (Williams and Sasaki [2005], Thollier and Jansen [2007]). The reason for such scarcity is that the information on the environmental footprint of chip manufacturing is also very scarce. This manufacturing phase is fundamental for the account of energy consumption, since it counts for a considerable amount of energy consumed during the production phase (Gotthardt et al. [2005], Williams and Sasaki [2005], Thollier and

[2]Recently, developed countries have been accused of exporting computer waste to places with looser environmental control (Niger, China or India) instead of providing a proper end-of-life treatment for such products. Greenpeace has denounced such abuses and launched the campaign "Hi-Tech: Highly toxic" (Greenpeace [2006])

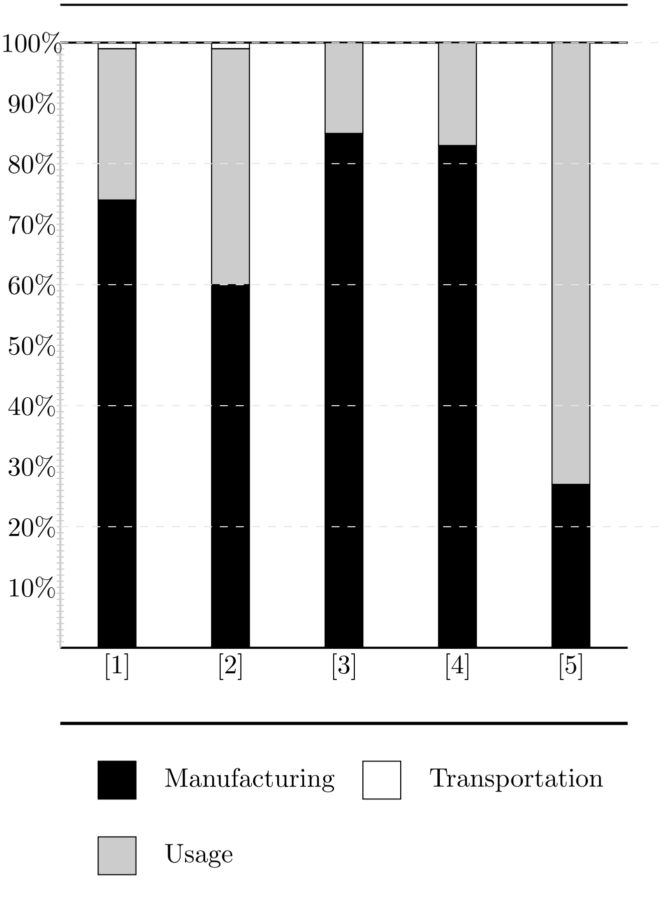

Figure 2.2: Cumulative Energy Demand (%) for the different phases of the life cycle of a personal computer. Data for production and usage were obtained from [1] Williams and Sasaki [2005], [2] Gotthardt et al. [2005], [3] Choi et al. [2006], [4] Williams et al. [2002] and [5] Atlantic Consulting and IPU [1998]. Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

Table 2.1: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer. The analysis includes the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund [2007]). ^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment. $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^\diamond$
Manufacturing				
Williams [2005] and BUWAL-250	240^l	$5,040^l$	$74^{c(l,e)}\%$	$4.67^{c(l)}$
Gotthardt et al. [2005] and BUWAL-250	$129^{c(l)}$	$2,700^l$	$60^{c(l,e)}\%$	$2.50^{c(l)}$
Choi et al. [2006] and BUWAL-250	N.A.	N.A.	$85^l\%$	N.A.
Atlantic Consulting and IPU [1998]	172^l	$3,630^l$	$26^l\%$	$3.36^{c(l)}$
Williams [2004]	290^l	$7,320^l$	$83^l\%$	$6.77^{c(l)}$
Usage				
Williams [2005] and BUWAL-250	80^l	$1,680^l$	$25^l\%$	$1.02^{c(l)}$
Gotthardt et al. [2005] and BUWAL-250	$83^{c(l)}$	$1,740^l$	$39^{c(l,e)}\%$	$1.61^{c(l)}$
Dell [2007a]	$93^{c(l)}$	$1,960^l$	N.A.	$1.81^{c(l)}$
Choi et al. [2006] and BUWAL-250	N.A.	N.A.	$15^l\%$	N.A.
Apple [2007c]	$89^{c(l)}$	$1,872^l$	N.A.	1.80^l.
Dell [2007b]	N.A.	N.A.	N.A.	6^l
Atlantic Consulting and IPU [1998]	$485^{c(l)}$	$10,200^l$	$74^l\%$	$9.43^{c(l)}$
TIAX LLC [2006]	78^l	$1,656^l$	N.A.	$1.53^{c(l)}$
Williams [2004]	N.A.	$1,500^l$	$17\%^l$	$1.39^{c(l)}$
Transportation				
Williams [2005] and BUWAL-250	$1.4^{c(e,l)}$	28^e	1%	≤ 0.10
Gotthardt et al. [2005] and BUWAL-250	$1.4^{c(e,l)}$	28^e	1%	≤ 0.10

Jansen [2007]). Information about the environmental footprint of chip manufacturing has been recently accounted in Williams et al. [2002].

We base our analysis on the results obtained by Atlantic Consulting and IPU [1998], Williams et al. [2002], Williams [2004], Williams [2005], Gotthardt et al. [2005], Choi et al. [2006], , TIAX LLC [2006] and the webpages of computer manufacturers (i.e. Apple [2007a] and Dell [2007a]). The reasoning behind using mixed sources from scientific literature, technical reports by independent firms, and technical reports from OEMs is to be able to triangulate the results from different sources.

According to Williams [2005], a total of 240kg of fossil fuel is used to produce a computer. As a comparison, Williams [2005] provides the following data: an automobile requires 2,000kg of fossil fuel to be produced, so the fossil fuel demand of a personal computer life cycle per year is approximately 60% of a car's fuel demand for production (per year). Another interesting comparison is the one with refrigerators. Considering that one changes one's computer every two years, and one's fridge every ten years, these two appliances consume approximately the same amount of energy during per year during their life time (Williams and Sasaki [2005], Williams et al. [1970]).

Contrary to most of the other electric appliances, the highest environmental burden of computers is due the production phase. The result concerning the proportional amount of energy consumed in manufacturing is resonant with those found in Williams [2004] Gotthardt et al. [2005], and Choi et al. [2006] (see figure 2.2). The results of Atlantic Consulting and IPU [1998] are dissonant with the aforementioned one. One possible explanation lies in the energy consumed during the usage phase, and in the increase in energy efficiency in the last ten years (see Apple [2007b] for an example of increasing energy efficiency for Apple computers). It is assumed in Atlantic Consulting and IPU [1998] that 10,200MJ are consumed during the usage phase. This value is much higher than the estimations found in Williams [2004], Gotthardt et al. [2005], and Choi et al. [2006].

The absolute values for energy consumption regarding the manufacturing phase found in Williams [2004] and Williams and Sasaki [2005] differ from the results found in Atlantic Consulting and IPU [1998] and Gotthardt et al. [2005] (see table 2.1 and figure 2.2). In Gotthardt et al. [2005], the analysis does not include the monitor. The analysis of Atlantic Consulting and IPU [1998] is possibly outdated, and does not reflect the manufacturing of similar equipments. The results, however, have the same order of magnitude and are still robust regarding the proportional participation of manufacturing on the total energy used, with the exception of Atlantic Consulting and IPU [1998].

According to Williams [2005], the usage phase is responsible for only 25% of the computer's environmental burden. The result is similar to those found in Williams [2004], Gotthardt et al. [2005], and Choi et al. [2006] (see figure 2.2). The absolute amounts of energy used found in the different studies are very similar, except for the work of Atlantic Consulting and IPU [1998]. The results for energy consumption found in Williams [2004], Gotthardt et al. [2005], Williams and Sasaki [2005], TIAX LLC [2006], Apple [2007b], Dell [2007a], and vary from 1,500MJ to 1,872MJ, or less than 25% from the lowest to the highest estimation. Again, the divergence found in Atlantic Consulting and IPU [1998] may be caused by the fact that the LCA is much older than the aforementioned ones.

Note that the transportation phase's environmental impact is negligible if compared to the complete life cyle's environmental impact. It is worth to mention, however, that transportation's impact may vary from irrelevant to small, depending on the assumptions made. For desktop computers, Williams and Sasaki [2005] suggest that transportation is not negligible: in a worst-case scenario of $5,000$km traveled by a 24kg computer, by truck, the energy consumed by transportation is estimated to be 680MJ, around 10 percent of the energy necessary to produce the computer, and approximately a 8% the energy consumed in the entire life cycle of the product. As pointed out by Williams and Sasaki [2005], the difference between the worst and the best case scenario for transportation's environmental impact might be tenfold.

The aforementioned results align with those found by Gotthardt et al. [2005]: in a desktop, the production phase is responsible for 60% of all the energy consumed, while usage consumes 39% and transportation around 1%. Choi et al. [2006] present similar results: 85% of the energy is consumed in the manufacturing phase, meanwhile 15% is used in the usage phase. Transportation is claimed to be irrelevant (Choi et al. [2006]).

It is important to note that although the production phase yields most of the environmental footprint, reclaiming such burdens via traditional bulk recycling is impossible. The reason for such apparent paradox lies in the semiconductors embedded in computers: the majority of the energy and raw material (and therefore waste) is used to produce the semiconductors, and very little can be claimed back via bulk recycling[3].

[3] For details on data, assumptions and calculations, see annexes.

An effective way to improve the life cycle of a computer is, therefore, to extend its life cycle. Doubling the life cycle from two to four years would cause a reduction of approximately 31% in the overall energy used. Re-selling, repairing, refurbishing and remanufacturing seem to be the effective alternatives to reclaim energy from personal computers. Furthermore, closing the loop with such activities might indeed help to mitigate the environmental impacts caused by computers. These results align with those found in Ruediger [2005].

Mobile phones

Mobile phone usage has also grown vertiginously in the last thirty years. The number has grown from a thousand status-symbol devices (e.g. see the scene in which Michael Douglas answers his mobile in the Bahamas in the 1987 movie Wall Street) to 2 billion ubiquitous convenience items in 2006. It is estimated that approximately 630 million mobiles[4] have been sold in 2004 (Singhal [2005]). In Europe alone, it is estimated that 105 million phones are replaced every year (FoneBak [2005]). Similar to the analysis for computers, we use different sources to enable triangulation of the results. We base our analysis on the results obtained by Schaefer et al. [2003], McLaren and Piukkula [2004], Gotthardt et al. [2005], Singhal [2005], and Frey et al. [2006]. These are technical reports by independent firms, technical reports from OEMs, and scientific papers. Results are presented in figure 2.3 and table 2.2.

The results for mobile phones resemble those for computers, although on average usage is a bigger factor for mobile phones that for computers. Gotthardt et al. [2005] show that most of the energy is used in the production phase. These findings are in resonance with those in McLaren and Piukkula [2004], Singhal [2005] and Frey et al. [2006]. They are also consistent with the results found by Nokia, using a more aggregated environmental measure (LCA Center [2007]). The results in Gotthardt et al. [2005] also show that the energy recovery of bulk recycling phase is irrelevant. Furthermore, the production phase is responsible for approximately 60% of the overall environmental impact, excluding transportation. In that case, however, transportation does not significantly contribute to the overall environmental impact. The environmental impact distribution of a mobile is presented in table 2.2 and in figure 2.3. Furthermore, in terms of absolute values, the estimations for CED in McLaren and Piukkula [2004], Singhal [2005], Frey et al. [2006] are very similar to each other.

[4] we use the terms “mobile” and “mobile phone” interchangeably

Table 2.2: Cumulative Energy Demand for the different phases of the life cycle of a mobile phone. FFD† is the fossil fuel demand in kg of fossil fuel.CED‡ is the cumulative energy demand. ◇ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund [2007]).^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment. $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs◇
Manufacturing				
Gotthardt et al. [2005] and BUWAL-250	N.A.	880^l	$59^{c(l)}$%	0.81
Singhal [2005]	$2.4^{c(l)}$	150^l	60^l%	0.12
Frey et al. [2006]	$8^{c(l)}$	$(132-165)^l$	$50^{c(l)}$%	0.15
McLaren and Piukkula [2004]	$7.6^{c(l)}$	160^l	$57^{c(l)}$%	0.15
Usage				
Gotthardt et al. [2005] and BUWAL-250	N.A.	587^l	$40^{c(l)}$%	0.55
Singhal [2005]	$1.2^{c(l)}$	77^l	29^l%	< 0.10
Frey et al. [2006]	$6^{c(l)}$	116^l	$41^{c(l)}$%	0.15
Schaefer et al. [2003]	N.A.	$94^{c(l)}$	N.A.	< 0.10
McLaren and Piukkula [2004]	$4.28^{c(l)}$	90^l	$32^{c(l)}$%	< 10
Transportation				
Williams [2005] and BUWAL-250	insignificant	insignificant	≤ 1%	< 0.10
Singhal [2005]	$0.5^{c(l)}$	28^l	11^l%	< 0.10
Frey et al. [2006]	$1^{c(l)}$	31^l	$9^{c(l)}$%	< 0.10
McLaren and Piukkula [2004]	$1.43^{c(l)}$	30^l	$11^{c(l)}$%	< 10

The reason why manufacturing dominates the energy consumption in mobiles seems to lie, as in computers, in their embedded electronic components, such as printed circuit boards for mobiles (Scharnhorst [2005]) and semiconductors, printed circuit boards and semiconductors in computers (Williams [2003]). Singhal [2005] shows that the production of the Wiring Board (PWB), Integrated Circuits (ICs), and Liquid Crystal Display (LCD) dominates the consumption during the life cycle of a mobile. For electronic equipment, therefore, little energy can be claimed via bulk recycling, but a substantial amount can be reclaimed via reuse, refurbishing or remanufacturing of used electronic equipments. Furthermore, extending the life time for computers and mobiles will also diminish the need for raw material.

The estimated proportional amount of energy used during the usage phase varies from 29% to 41%. The results regarding usage vary considerably, mainly due to the assumptions regarding the life span of the equipment and the number of hours used per year. Despite the significant differences between the estimations, however, the estimation of the amount of energy consumed in the usage phase is, for all cases, less than the estimated amount of energy consumed in manufacturing.

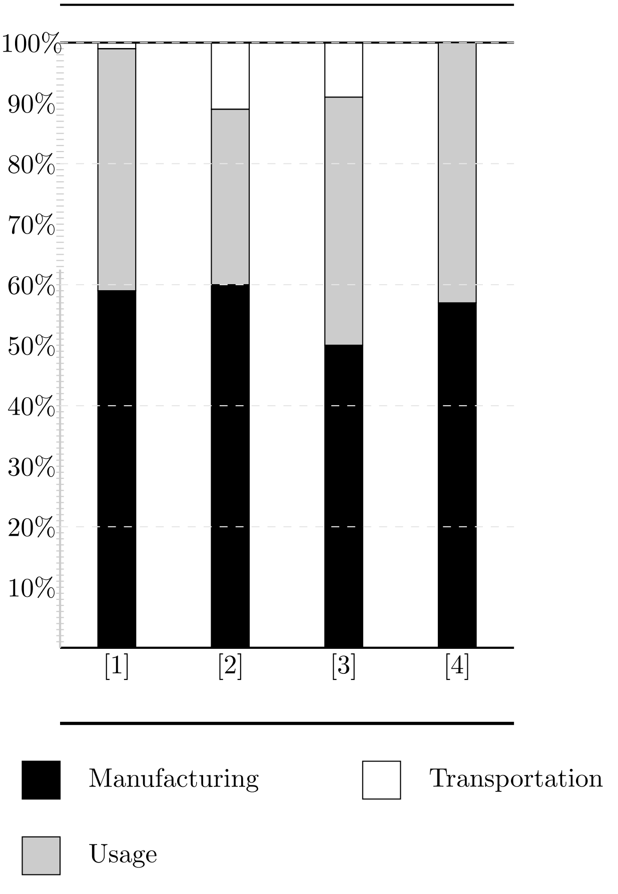

Figure 2.3: Cumulative Energy Demand (%) for the different phases of the life cycle of a mobile phone. Data for production and usage were obtained from [1] Gotthardt et al. [2005], [2] Singhal [2005], [3] Frey et al. [2006], [4] McLaren and Piukkula [2004] . Data regarding transportation has been estimated using BUWAL-250. See appendix for details.

The amount of energy used in transportation varies from insignificant to more than a tenth of the total energy consumed in the life cycle. Despite the variance within the estimations, for all of them transportation consumes significantly less energy than the other two phases.

2.5.2 Environmental impact of electrical products

Refrigerators

Information on the energy consumption for the different phases of the life cycle of electrical equipments, such as refrigerators, TV sets and washing machines are more abundantly available, if compared to the same information for electronics. For such equipments, the usage phase is responsible for most of the energy used during the life cycle of the product (Williams and Sasaki [2005], Steiner et al. [2005], LCAcenter [2005]).

The use of household refrigerators and freezers is one of the main sources of environmental impact for EEE. In refrigerators, however, usage is the activity that, by far, demands most of the energy (Williams [2005]). For a refrigerator, $1,330$kg of fossil fuel are consumed to produce and use a refrigerator, and 96% is consumed during its usage phase (Williams [2005]). Similar results are reported in Steiner et al. [2005], Kim et al. [2006] and Otto et al. [2006]. Table 2.3 and figure 2.4 portrait the energy consumption for this appliance.

Table 2.3: Cumulative Energy Demand for the different phases of the life cycle of a refrigerator. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund [2007]).^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g. transportation moment. $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED(%)	carbon offset costs$^\diamond$
Manufacturing				
Williams [2005] and BUWAL-250	53^l	$1,110^l$	4^l%	1.04
Steiner et al. [2005]	N.A.	N.A.	20^l%	N.A.
Kim et al. [2006] and BUWAL-250	$286^{c(l)}$	$6,000^l$	$5^{c(l)}$%	5.5
Otto et al. [2006] and BUWAL-250	$243^{c(l)}$	$5,100^l$	$7^{c(l)}$%	4.72
Horie [2004] and BUWAL-250	$283^{c(l)}$	$5,940^l$	$6^{c(l)}$%	5.49
Usage				
Williams [2005] and BUWAL-250	$1,277^l$	$26,813^l$	96^l%	24.8
Steiner et al. [2005]	N.A.	N.A.	80^l%	N.A.
Kim et al. [2006] and BUWAL-250	$5,400^{c(l)}$	$113,400^l$	$95^{c(l)}$%	105.5
Otto et al. [2006] and BUWAL-250	$3,071^{c(l)}$	$64,500^l$	$93^{c(l)}$%	59.66
Horie [2004] and BUWAL-250	$4,326^{c(l)}$	$90,860^l$	$94^{c(l)}$%	84.04
Transportation				
Williams [2005] and BUWAL-250	$9.6^{c(l)}$	$201^{c(l)}$	$1^{c(l)}$%	insignificant

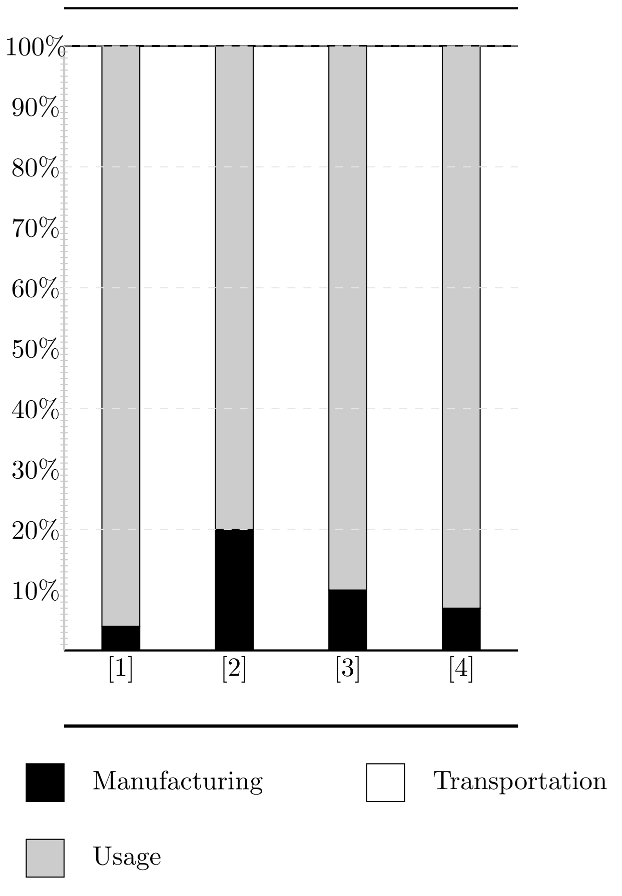

Figure 2.4: Cumulative Energy Demand (%) for the different phases of the life cycle of a refrigerator. Data for production and usage were obtained from [1] Williams [2005], [2] Steiner et al. [2005], [3] Kim et al. [2006], [4] Otto et al. [2006] . Data regarding transportation has been estimated using BUWAL-250. See appendix for details.

TV sets

The usage of TV is also a considerable source of environmental impact within the EEE group. The energy consumption profile of a TV is close to that of refrigerator. The usage phase for the TV is responsible for 89% of the overall CED (Behrendt et al. [1997]). The impact of recovery for TVs also seems quite limited. Similar results are reported in Alting et al. [1997], Steiner et al. [2005], Takayoshi et al. [1999] and Sony

[2008]. For TVs, the CED distribution for production, transportation and usage is represented in table 2.4 and figure 2.5.

Table 2.4: Cumulative Energy Demand for the different phases of the life cycle of a Tv set. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund [2007]).^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^\diamond$
Manufacturing				
Steiner et al. [2005]	N.A.	N.A.	20^l%	(-)
Alting et al. [1997]	$222^{c(l)}$	$4,667^l$	$22.6^{c(l)}$%	4.31
Feng and Qian Ma [2008]	$454^{c(l)}$	$9,542^l$	$22.88^{c(l)}$%	8.83
Takayoshi et al. [1999]	N.A.	N.A.	20^l%	N.A.
Sony [2008]	N.A.	N.A.	13^l%	N.A.
Usage				
Steiner et al. [2005]	N.A.	N.A.	80^l%	(-)
Alting et al. [1997]	$762^{c(l)}$	$16,000^l$	$77.4^{c(l)}$%	14.8
ACE [2008]	$317^{c(l)}$	$6,660^l$	N.A.	6.16
Sony [2008]	N.A.	N.A.	87^l%	N.A.
Takayoshi et al. [1999]	N.A.	N.A.	80^l%	N.A.
Feng and Qian Ma [2008]	$1148^{c(l)}$	$24,115^l$	$57.50^{c(l)}$%	22.30
Transportation				
Alting et al. [1997]	(-)	$< 400^l$	insignificant	¡0.10
Sony [2008]	N.A.	N.A.	insignificant	
Feng and Qian Ma [2008]	$395^{c(l)}$	$8,280^l$	$19.7^{c(l)}$%	7.66

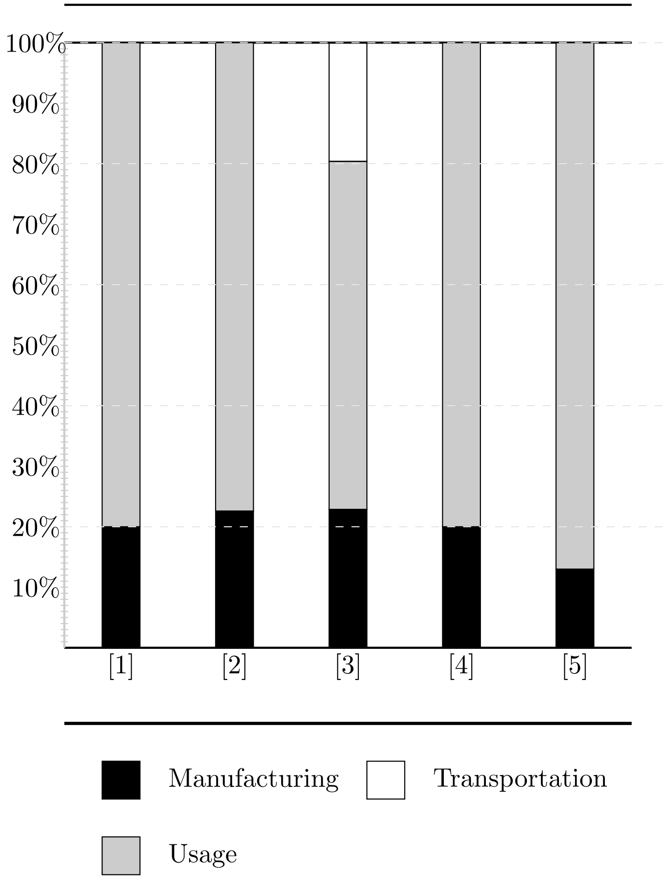

Figure 2.5: Cumulative Energy Demand (%) for the different phases of the life cycle of a TV set. Data for production and usage were obtained from [1] Steiner et al. [2005], [2] Alting et al. [1997], [3] Feng and Qian Ma [2008], [4] Takayoshi et al. [1999] and [5] Sony [2008]. Data regarding transportation has been estimated using BUWAL-250. See appendix for details.

Washing machines

The results for washing machines resemble those from the other electrical appliances. Usage is the phase that most consume energy. Manufacturing and transportation consume much less energy than usage. Figure 2.6 and table 2.5 illustrate the results.

Table 2.5: Cumulative Energy Demand for the different phases of the life cycle of a washing machine. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund [2007]).^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^\diamond$
Manufacturing				
Steiner et al. [2005]	N.A.	N.A.	14^l%	N.A.
LCAcenter [2005]	N.A.	N.A.	24^l%	N.A.
Otto et al. [2006]	$1,965^{c(l)}$	$6,100^l$	$8^{c(l,e)}$%	$5.64^{c(l)}$
Throne-Holst et al. [2007]	*N.A.*	*N.A.*	$\leq 10^l$%	N.A.
Usage				
Steiner et al. [2005]	N.A.	N.A.	86^l%	N.A.
LCAcenter [2005]	N.A.	N.A.	76^l%	
Otto et al. [2006]	$3,371^{c(l)}$	$70,800^l$	$92^{c(l,e)}$%	$65.5^{c(l)}$
Throne-Holst et al. [2007]	*N.A.*	*N.A.*	$\geq 90^l$%	N.A.
Transportation				

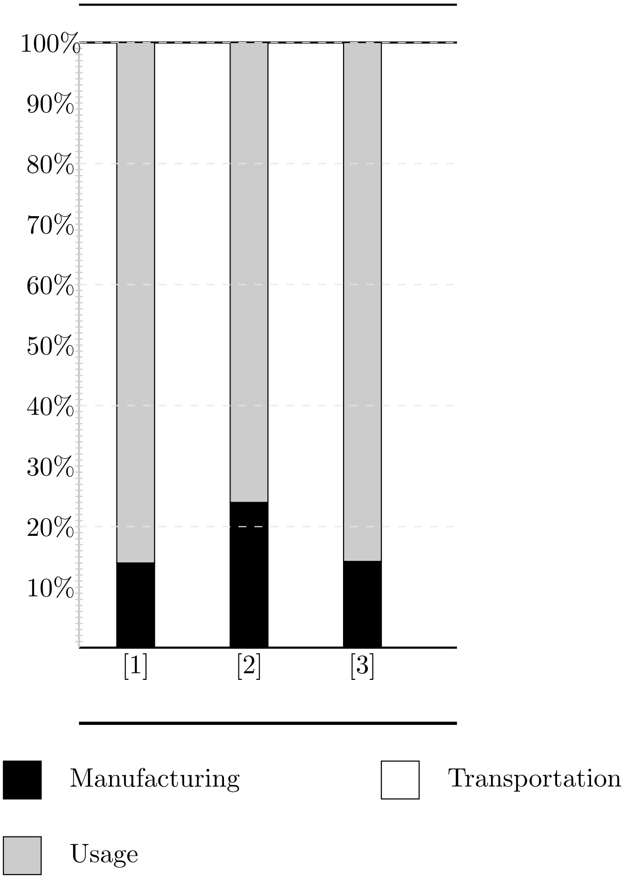

Figure 2.6: Cumulative Energy Demand (%) for the different phases of the life cycle of a washing machine. Data for production and usage obtained were obtained in [1] Steiner et al. [2005], [2] LCA Center [2007], [3] Otto et al. [2006]. Data regarding transportation has been estimated using BUWAL-250. See appendix for details.

The results for electric equipments, more specifically refrigerators, washing machines, and TV sets show that the consumption of energy is concentrated in the usage phase. Little in terms of energy can be recovered via the adoption of better end-of-life decisions. The results, however, must be interpreted with care. We do not claim that bulk recycling will not significantly improve the overall environmental performance of the aforementioned electric equipment. We cannot assume, however, that extending the life cycle of those equipments will render positive effects for the environment (increase energy demand versus decrease in resources depletion, for instance), as it seems to be the case for electronic equipment.

2.6 Interpretation of the results

In the previous section, the data regarding energy usage refer to the different phases of the life cycle of the products. In order to test our hypotheses, it is necessary to make further assumptions regarding the life span of the new and remanufactured products, the energy required to remanufacture these equipments, and the change in energy profile from a new to a remanufactured equipment.

Different assumptions regarding the aforementioned parameters reflect, at a large extent, different reverse supply chains. Consider, for example, remanufacturing fridges with an outdated technology. In this case, it is reasonable to assume that the average life span of these remanufactured appliances are shorter than the average life span of their new counterparts, that they consume much more energy, etc. In this section, we are interested in analyzing the environmental gains of remanufacturing of products that are, functionally, identical to their new counterparts. Our assumptions are:

- The average life span for the remanufactured products is the same as the average life span of the new counterparts.
- There energy efficiency of the remanufactured products is the same as the energy efficiency of the new products.
- The energy required to remanufacture these products equals 20% of the energy used to manufacture them.

The first and second assumptions indicate that we are addressing remanufactured products that are, essentially, as good as new. The third assumption is also based on the assumption that the remanufactured appliances are identical to the newest versions, and therefore need no upgrade.

Regarding RQ1, we analyzed the following hypothesis:

> H1.1: For computers and mobiles, raw material extraction and manufacturing are the phases in the life cycle that consume more energy. Usage is second, and transportation is the phase that is least energy intensive.
>
> H1.2: For refrigerators, washing machines and TV sets usage is the phase in the life cycle that consumes more energy. Raw material extraction and manufacturing are second, and transportation is the phase that is least energy intensive.

According to the analysis presented in the previous sections, hypothesis H1.1. cannot be rejected. For the electronic products analyzed (computers and mobiles) manufacturing, usage and transportation are, in this order, the phases with higher energy consumption.

Hypothesis H1.2 is also not rejected. For the electrical products (refrigerator, TV set, washing machine) usage, manufacturing and transporting are, in this order, the phases with higher energy consumption.

Regarding RQ2, we have the following hypotheses:

> H2.1: For computers and mobile phones, reuse, refurbishing and remanufacturing substantially diminish the energy used in the life cycle of the product.

In order to test this hypothesis, we need some further assumption. As mentioned previously, we assume that the reused, refurbished, and remanufactured products are equivalent to the new product. It means we assume the same life span and the same energy consumption. Secondly, we assume that neither refurbishing nor remanufacturing will consume more than 20% of the energy used for remanufacturing. Given the following assumptions, it is easy to see that extending these activities will significantly diminish the total energy consumed during the life cycle of the product.

> H2.2: For computers and mobile phones, reuse, refurbishing and remanufacturing substantially diminish the waste stream in the life cycle of the product.

Given the fact that we are analyzing the waste generated by the end-of-life of the the products, every reused, refurbished and remanufactured product saves exactly one product from being disposed. Reusing, refurbishing and remanufacturing effectively reduces the waste generated by electronic equipments.

Regarding electrical equipments:

> H2.3: For refrigerators, washing machines and TV sets reuse, refurbishing and remanufacturing do not substantially diminish the energy used in the life cycle of the product.

This hypothesis is clearly not rejected. For refrigerators, the studies of Williams and Sasaki [2005], Steiner et al. [2005], Kim et al. [2006], and Otto et al. [2006]

clearly show that increasing the life-time for such components would not substantially decrease the CED of the entire life cycle of the product. The same is valid for TV sets and washing machines. For TV sets, Alting et al. [1997], Takayoshi et al. [1999], Steiner et al. [2005], and Sony [2008] shows that the energy consumption of the usage phase is also much higher than the consumption of the manufacturing and distribution phase. The results of the four aforementioned LCAs are very well aligned regarding the percentage of energy consumed during the usage phase. Alting et al. [1997], Takayoshi et al. [1999], and Steiner et al. [2005], and Sony [2008] have found that the energy used during the usage phase is, respectively 77.4%, 80%, 80% and 87% of the total energy consumed during the life cycle of the product. For washing machines, the results are similar. Steiner et al. [2005], LCAcenter [2005], and Otto et al. [2006] found that the usage phase is responsible for, respectively, 86%, 76%, and 92% of the energy consumed during the entire life cycle. The results are as expected [5]

The reuse, refurbishing and remanufacturing of older equipments (with lower energy efficiency) would decrease the waste produced, but it would also increase CED. These activities would undoubtedly decrease CED only if performed in the latest models.

> H2.4: For refrigerators, washing machines and TV sets reuse, refurbishing and remanufacturing substantially diminish the waste stream in the life cycle of the product.

For H2.4. we use the same analysis as in H2.2. Reuse, remanufacturing and refurbishing will, therefore, prevent the aforementioned electrical appliances from being diverted to the waste stream.

2.7 Implications of the results

The implications of these results for the OM community, as well as for the design of recovering supply chains, is that for electronics remanufacturing levels can be used as a good indicator for sustainability. In other words, the more electronics are remanufactured, the better for the environment. Furthermore, regarding energy use and

[5] We assume that the remanufactured appliances are as energy efficient as the new models. Even with such assumption, we have shown that remanufacturing does not substantially reduce the energy used during the life cycle of these products. Furthermore, the reuse, refurbishing and remanufacturing of older equipments (with lower energy efficiency) could decrease the waste produced, but it would also increase CED.

material recovery, the decision on whether to refurbish or remanufacture is the most relevant one. Another way to assess the sustainability of the system is to calculate the amount of remanufactured equipment. This can be done by approximation, using data in databases, and books. Furthermore, it is possible to storage such information in RFIDs in a form of a remanufacturing bill, similar to the recycling bill developed in Spengler and Stolting [2003] for recycling materials. Table 2.7 summarizes the findings.

main solutions (waste,CED)	*computers and mobiles*	refr., wash. mach. and TV
reuse	*+,+*	*+,-*
refurb. and remanuf.	*+,+*	*+,-*

Table 2.6: Potential mitigation of the environmental footprint of electrical and electronic products due to recovering activities. "+" indicates positive impact. "-" indicates negative impact.

Furthermore, since remanufacturing and refurbishing are the activities that can potentially mitigate most of the environmental impact during the life cycle of electronic products, the decision on whether to remanufacture or not is crucial for the environment. There also seems a good place to look for good and significant trade-offs between business and the environment. Engaging in economic-neutral remanufacturing activities is a promising way to mitigate environmental impact. Raising the level of remanufacturing, as well, may render a significant reduction in the environmental impact of electronic equipments at a good price. Another conclusion is that recycling targets, as proposed in the WEEE can not, in general, mitigating the environmental footprint of such equipments.

For electrical equipments, the result is that remanufacturing and refurbishing can diminish the waste generated, but can also substantially increase the energy used in the life cycle.

For the electronic equipments described in this section, increasing the life-span can potentially decrease the total energy consumed during they life cycle. Closing the loop for such products, therefore, is indisputably good for the environment, as it is commonly found in the CLSC literature.

Chapter 3

Designing and evaluating eco-efficient recycling networks

3.1 Introduction

As previously discussed in the second chapter, consumers and legislation have pushed OEMs of electrical and electronic products to re-think their supply chains in order to mitigate their environmental impact. A number of initiatives may help to diminish the impact on the environment, such as adopting green procurement, engaging in remanufacturing or reducing transportation.

In this chapter we focus on the design of the recovery network for used products. The recovery network is the part of the logistic network concerned with the recovery of the products and the subsequent re-direction to other consumers or to the end-of-life of these products. More specifically, we focus on the network design of reverse supply chains concerning end-of-life (i.e. recycling, landfill and incineration). The recovery part of the supply chain has a significant impact on the total cost of the supply chain, as well as on its environmental footprint. Loosely speaking, the reason why the recovery network for recycling, landfilling and incineration is so important lies in its volume. The flow of collected end-of-life products is mostly oriented on recycling, landfills and incineration, and only a small fraction of it is reverted back to the supply chain, as refurbished or remanufactured products. In spite of the enormous potential for energy and material recovery, as we showed in the second chapter, few used electronic and electric equipments are remanufactured. The reason is prosaic: in the market arena of electronics most of the collected equipments do not stand a chance against the new models. A ten year old computer, a five year old mobile and a walkman, for instance, are in most places considered completely obsolete equipment, and have, therefore, no market. The destination after use for these equipment is in most cases, final.

Regarding this final destination, different locations and types of recycling render different solutions for business and the environment. Take the level in which an equipment is recycled, for example. After cleaning the tube of TVs and monitors, for instance, the glass can be safely disposed or recycled. Some manufacturing facilities, however, do not recycle glass. In order to have this fraction of material recycled they need to transport it to some other recycling facility. In many situations, it is more convenient, and overall cheaper, to dispose the glass on the nearest landfill, since landfills are more abundant than recycling facilities. From this small example, it is easy to see that the myriads of products and the number of end-of-life solutions for each of these products render a large number of different levels of profit, waste and energy recovery. The complexity of the system points to the usage of optimization techniques to determine the best solutions concerning profit and mitigation of waste, as well as reclamation of energy.

The other important point in question is the efficiency of existing networks regarding waste, energy recovery and profit. The question is relevant in determining the efficiency of existing recovery networks, and verify whether re-configurations would yield better results and. In other words, we intend to check how efficient the existing models are, compared to the theoretical optimal frontier for this problem.

The objective of this chapter is to contribute to the design of sustainable recovery logistics networks balancing *planet* and *profit*, and to evaluate the efficiency of existing networks. We begin with a brief literature review of eco-efficiency and recovery logistics networks. The problem we approach is situated within the literature of the aforementioned topics, as depicted in figure 3.1. Furthermore, we discuss how the use of MOP to design sustainable supply chains helps to assess the trade-offs between the logistics network cost and its environmental impact, as well as to calculate the efficiency of existing logistics networks. We also discuss the expected CPU-time difficulties regarding a MOP approach for the design of sustainable logistics networks. Finally, we propose our method to assess the efficiency of existing logistics networks.

This chapter is divided as follows. In Section 3.2 we review the main literature on eco-efficiency. In Section 3.3 we review the relevant literature on the design of reverse supply chain networks. In Section 3.4 we present the formulation for the

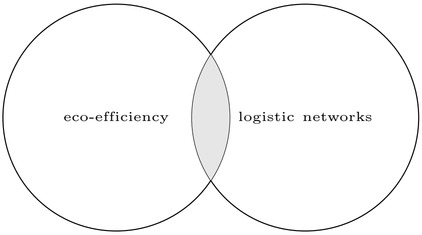

Figure 3.1: Relevant literature for Chapter 3. The shaded area represents the part of the literature to which we contribute.

design of supply chain recovery networks, concerning the minimization of costs and environmental footprint. In Section 3.5 we present the computational difficulties to find all non-dominated solutions for the formulation proposed. In Section 3.6 we also motivate our decision regarding which methodology to use, based on CPU-time and on the possibility to assess the trade-offs between the environmental (i.e. waste and energy) and the business dimension (i.e. costs). In Section 3.7 we provide a simple tool to evaluate Pareto efficiency of recovery networks, using DEA techniques and MOP.

3.2 A literature review on eco-efficiency

The idea of an efficient frontier for eco-efficiency was first presented by Huppes and Ishikawa [2005]. They also proposed the concept of an eco-frontier with the "optimum" or preferred solution defined by society. The idea of eco-efficiency and its measurement has been explored by Chung and Fare [1997], Boyd and McClelland [1999], Dyckhoff and Allen [2001], Bevilacqua and Braglia [2002], Fare et al. [2004], Arcelus and Arocena [2005], Kobayashi et al. [2005], Scholz and Wiek [2005], Kortelainen and Kuosmanen [2007] Sarica and Or [2007] and Zhou et al. [2007]. The aforementioned papers use mainly two techniques to evaluate efficiency.

A first technique consists of using simple ratios (e.g. amount of economic value added (EVA) per ton of carbon) to assess eco-efficiency. Hellweg et al. [2005] propose a method based on the differences between the differences in associated costs divided by environmental impact indices for different projects. The methodology is only suitable for a discrete number of possible solutions. Scholz and Wiek [2005] propose a similar approach, also based on ratios. They calculate operational eco-efficiency as the improvement of economic utility divided by the improvement in environmental utility. The project under consideration is compared to the business-as-usual alternative. Kuosmanen and Kortelainen [2005] define eco-efficiency as the ratio of total value added and a damage function, aggregating environmental pressures into a single damage score.

A second technique uses DEA to evaluate efficiency. Fare et al. [2004], Kobayashi et al. [2005], and Kortelainen and Kuosmanen [2007] use DEA to provide a single measure. A vast number of other environmental studies also make use of DEA (Chung and Fare [1997], Boyd and McClelland [1999], Dyckhoff and Allen [2001], Bevilacqua and Braglia [2002], Fare et al. [2004], Arcelus and Arocena [2005], Sarica and Or [2007], Zhou et al. [2007]) without, necessarily, mentioning the term eco-efficiency. A survey of DEA in environmental studies (and energy) is presented in Zhou et al. [2008].

The above methodologies share two common characteristics. First, they provide a single efficiency measure and implicitly assume the solution with the best ratio is preferred. Second, they are applied to a discrete and small set of possible solutions, mainly to the selection of projects or technologies, whereas most combinatorial optimization problems have many variables and millions of possible solutions. Figure 3.2 portrays the methodology using a single ratio. Note that the alternative black dots, i.e. representing different projects or technologies, serve as inputs for the model. The frontier itself does not map a real solution in this case.

The methodologies described above are applied to a small and discrete set of possibilities or alternatives (e.g. different alternatives for the design of a product (Otto et al. [2006])). Krikke et al. [2003] use the concept of weighted sum scalarization, which also uses a single measure to define the best solution regarding environmental and costs objectives, but applied to a continuous set of alternatives. Specifically, the problem proposes a recovery network design for the recovery of refrigerators. Krikke et al. [2003] provide three efficiency measures to describe eco-efficiency, i.e. costs, energy use and waste. This is, to the best of our knowledge, the only paper that explores the concept of eco-efficiency concerning the design of recovery networks. The authors use weights to explore the efficient solutions in terms of the environment and business. They rely on the assumption that a weighting process captures the preferred solution for business and the environment. Figure 3.3 illustrates such procedure, which in the DEA stream of research, is called Preference Structure Methodology (Zhu [1996]). In the MOP field of research, it is called the weighted sum method. Note that in the case of weighted sum methods, the black dots are supported efficient

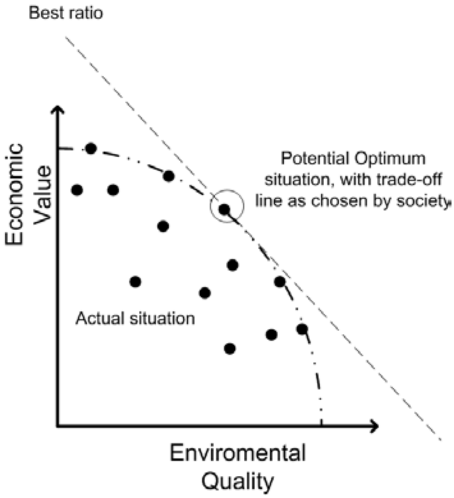

Figure 3.2: The Single Ratio method

solutions of the proposed model (for the definition of supported solutions see Ehrgott and Gandibleux [2000]). For the Preference Structure methodology, the black dots are Decision Making Units (DMUs). Changing the weights in order to explore the efficient frontier may lead to an unbalanced exploration, with some regions being well explored while others are left completely untouched. The disadvantages of using weights to select the preferable efficient solution is extensively documented in the MCDM literature. The early seminal works in the field have already documented such disadvantages (Zeleny [1974], Zionts and Wallenius [1976], Steuer and Choo [1983]).

The weighted sum approach in Krikke et al. [2003] and the formulations using a single ratio share two common characteristics. The first is that these methods do not address the exploration of the efficient frontier or the respective calculation of trade-offs. The second is that they assume that the eco-efficient ratio or the weighting procedure captures the decision makers' preferred solution(s).

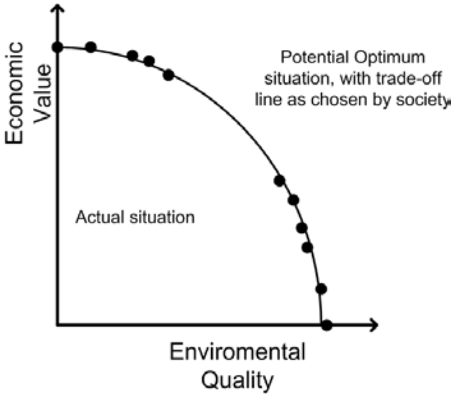

Figure 3.3: The Weighted sum method (also called Preference Structure Method)

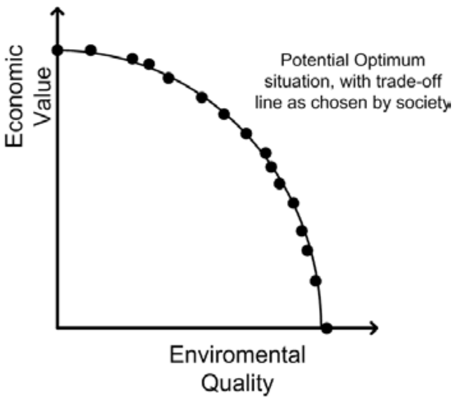

Figure 3.4: The multiobjective method

3.3 A literature review on recovery networks

The decisions on the supply chain network design are very important at a strategic level. They include decisions such as (i) which recovery facilities should be used or opened? and (ii) which costumers will these facilities serve? (Melo et al. [2008]). These problems have received a lot of attention in the fields of Operations Research and Logistics. The literature in location analysis is composed by hundreds of papers (ReVelle and Eiselt [2005]). We suggest the reading of Drezner [1995], ReVelle and Eiselt [2005] and Melo et al. [2008] for reviews.

In the last decades, a growing attention has been given to the design of recovery networks. These networks are dedicated to the collection and recovery (e.g. refurbishing, remanufacturing) and/or end-of-use activities (i.e. recycling, energy recovery). The recovery network includes decisions regarding (i) where to locate recovery facilities, such as disassembly and remanufacturing centers, (ii) which customers, plants or warehouses should be served by these recovery facilities?, and (iii) which recycling and disposal facilities should receive the products that are not returning to the supply chains?

A flurry of investigations regarding the design of recovery networks have appeared in the main journals of Operations Management and Operations Research. Kroon and Vrijens [1995], Ammons et al. [1997], Berger and Debaillie [1997], Spengler et al. [1997], Thierry [1997], Barros et al. [1998], Krikke et al. [1999], Jayaraman et al. [1999], Louwers et al. [1999], Realff et al. [1999], Fleischmann [2000], Shih [2000], Fleischmann et al. [2001], Sodhi and Reimer [2001], Jayaraman et al. [2003], Krikke et al. [2003], Baumgarten et al. [2004], Beamon and Fernandes [2004], de Blanc et al. [2004], Aras et al. [2007], Min et al. [2006a], Min et al. [2006b], Du and Evans [2007], , Gomes Salema et al. [2007], Kaka et al. [2007], Ko and Evans [2007], Lieckens and Vandaele [2007], Listes [2007], Salema et al. [2006], Srivastava [2008] and Walther et al. [2007] are examples.

Fleischmann [2000] characterizes recovery networks as recycling networks, remanufacturing networks, and reusable item networks. Remanufacturing networks are devoted to the collection, testing, and remanufacturing activities. These networks are concerned with the reuse of valuable products and their parts (Fleischmann et al. [2001]). The design of remanufacturing networks involves the decision on where to locate collection centers (Fleischmann [2000], Jayaraman et al. [2003], de Blanc et al. [2004], Min et al. [2006b], Aras et al. [2007]), warehouses (Fleischmann [2000], Beamon and Fernandes [2004] , Ko and Evans [2007]), disassembly centers (Fleischmann et al. [2001]) and remanufacturing facilities (Jayaraman et al. [1999], Fleischmann et al. [2001], Jayaraman et al. [2003], Beamon and Fernandes [2004], and Ko and Evans [2007]). The design of recovery networks has been studied by Jayaraman et al. [1999], Krikke et al. [1999], Fleischmann [2000], Fleischmann et al. [2001], Beamon and Fernandes [2004], Min et al. [2006b], Min et al. [2006a], Du and Evans [2007], and Srivastava [2008].

The recycling networks are devoted to the collection, recycling and proper disposal of used equipments. The objectives of these networks are to reclaim raw material and energy, and to provide their proper disposal. Products that are not reverted back to

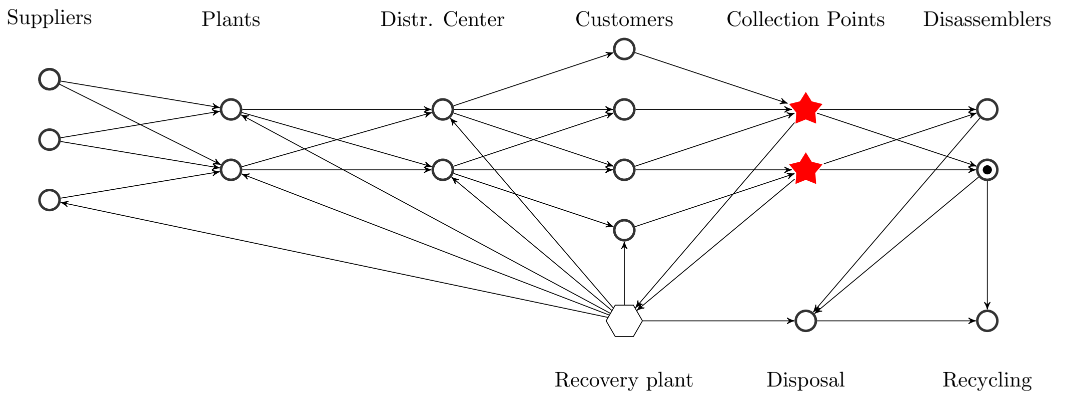

Figure 3.5: Generic forward, remanufacturing and recycling network.

the market in the remanufacturing networks are diverted to the recycling networks. The location-allocation decisions for these networks include the location of collection points (Louwers et al. [1999]), recycling facilities (Barros et al. [1998], Louwers et al. [1999], Shih [2000], Krikke et al. [2003], Spengler et al. [1997]), warehouses (Shih [2000]). The design of recycling networks have been studied by Barros et al. [1998], Louwers et al. [1999], Realff et al. [1999], Spengler et al. [1997], Shih [2000], Krikke et al. [2003]. Figure 3.5 illustrates both the remanufacturing and recycling networks[1].

This chapter focuses on the design of recovery networks. The contribution of our formulation is to incorporate environmental dimensions into the problem. The aforementioned literature in the field is dedicated to the problem of minimizing the costs of the network, and does not consider the environmental footprint as an objective to be minimized. We are interested, however, in Pareto optimal solutions concerning costs, energy recovery and waste, and not in the cost minimization problem only. Furthermore, we are interested in the relations between the economic and environmental relations, and their trade-offs.

In more detail, the contribution in this chapter is threefold: (i) introduce the design of a recycling network taking into account cost, energy demand and waste, (ii) show how to efficiently solve the problem of recycling networks in which waste, energy and costs must be minimized, and (iii) create an efficiency measure for the existing recycling network.

[1]Networks for reusable items are less studied in the literature, and for this reason we leave their description out of this manuscript. For more information on reusable networks, see Fleischmann [2000]

3.4 Pareto efficient recycling networks in terms of the environment and costs

The recycling networks are responsible, as previously discussed, for the recycling, energy recovery and proper disposition of end-of-use equipments. These networks play an important role in the elimination of harmful substances, and the recovery of raw materials and energy, and in the mitigation of the disposed waste. Recycling reclaims raw materials, such as metals, with a fraction of the energy needed to produce them. Furthermore, since these products will be reverted to the supply chain, recycling mitigates the flow of material that is landfilled. Incineration is also a form of energy reclamation. Materials, such as plastics, are burned and energy is generated from the process. Furthermore, as it occurs in recycling, the waste that would end in landfill is also diverted. On the other hand, energy is consumed during the transportation of these materials, from the collection point to disassembly, recycling and final disposition.

Different levels of energy recovery, waste mitigation and costs of a recycling networks are associated with its design. Different networks, therefore, render different outcomes concerning energy and waste, and have different costs. Take the following example. Installing collection points and disposal sites close to the consumption centers is likely to increase costs, due to the higher costs of land in these centers. The energy necessary to transport end-of-use equipments from the consumer centers to the aforementioned sites is, however, smaller. This reduction in transportation, *ceteris paribus*, diminishes energy usage. Increasing the level of recycling mitigates waste and increases energy recovery from the materials, but is likely to increase transportation and therefore increase energy consumption. Increasing the levels of recycling may also increase the costs associated with the recycling network.

The mitigation of waste, the use of energy in the network and the associated costs of this network are thus clearly potentially conflicting objectives. The conflict between the objectives, the number of different recycling network alternatives, as well as the complexity of the problem call for an MCDM approach. We formulate the problem of the recycling network as a multi-objective one.

The following model is an extension for the recycling networks design problem, with the inclusion of energy and waste minimization as objectives. The model is based on observations of the recycling networks in Germany, and was first proposed by Walther and Spengler [2005] and Walther [2005]. Furthermore, Walther and Spengler [2006] proposes the same formulation and approach the problem using weighted Goal

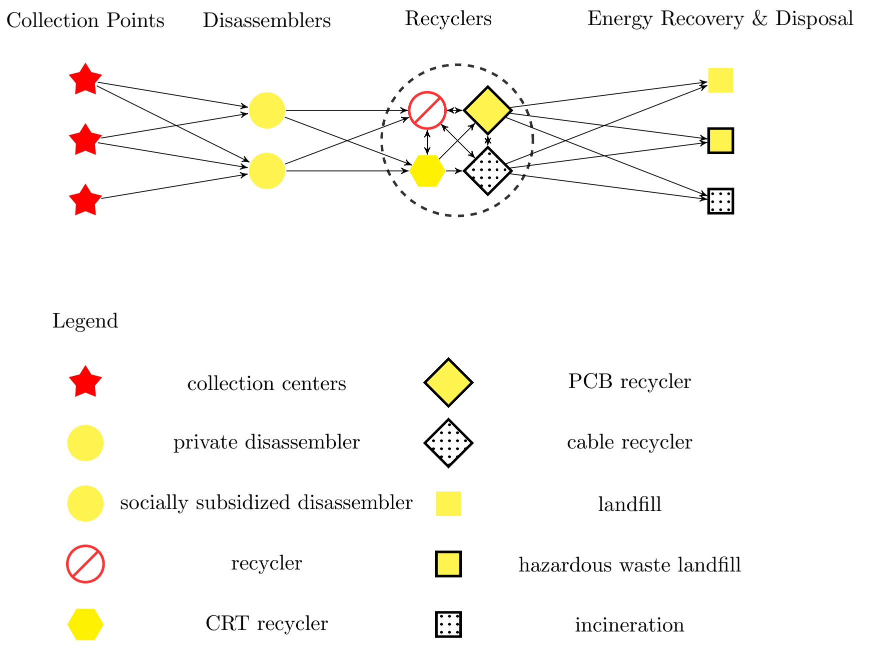

Figure 3.6: German recycling network

Programming (WGP). The formulation used here is identical to the formulation in Walther and Spengler [2005].

In the recycling systems in Germany, the collection points are the municipalities. Furthermore, disassembling, recycling, and disposal are predominantly outsourced (Walther and Spengler [2005]). The decision for the OEM is, therefore, where to allocate the streams of waste from the municipalities, and which types and levels of recycling, incineration and disposal should be pursued. Figure 3.6 illustrates the German Recycling Network. Mathematically, our problem is therefore reduced to a linear MOP.

Indices and Sets:

i	products and materials ($i \in I$)
j	recycling operations ($j \in J$)
u	recycling companies ($u \in U$)
r	recovery/disposal facilities ($r \in R$)
q	collection points ($q \in Q$)

Decision variables:

y^D_{iu}	mass of material type i after disassembly at treatment company u
y^Q_{iqu}	mass of discarded product type i delivered from collection point q to recycling company u
y^R_{iur}	mass of material type i delivered from recycling company u to recovery/disposal facility r
x_{ju}	number of executions of recycling operation j in recycling company u
$y^U_{iuu'}$	mass of discarded product type i delivered from recycling company u to recycling company u'

Parameters:

v_{ij}	recycling operation coefficient representing input(-)/output(+) masses of product/material type i consumed/caused by one execution of recycling operation j
e^A_i	acceptance fees, the network gets for treating one kilogram of product type i
c^Q_{iqu}	costs for transportation of one kilogram of material type i from collection point q to recycling company u
$c^U_{iuu'}$	costs for transportation of one kilogram of material type i from recycling company u to recycling company u'
ced^Q_{iqu}	CED for transportation of one kilogram of material type i from collection point q to recycling company u
ced^R_{iur}	CED for transportation of one kilogram of material type i from recycling company u to recovery/disposal facility r

$ced^{U}_{iuu'}$	CED for transportation of one kilogram of material type i from recycling company u to recycling company u'
ced^{Z}_{ju}	CED for recycling activity j at recycling company u
e^{V}_{ir}	sales revenue(+)/disposal cost(-) for delivery of one kilogram of material type i to recovery/disposal facility r
c^{R}_{iur}	costs for transportation of one kilogram of material type i from recycling company u to recovery/disposal facility r
c^{Z}_{ju}	costs for the application of one recycling operation j in recycling company u
rec_{ir}	fraction of material type i that was sent to recovery facility r approved to be recycled
y^{QMAX}_{iq}	mass of product type i that has to be collected at source q
y^{RMAX}_{ir}	capacity available at recovery/disposal facility r
C^{ZMAX}_{u}	capacity available at recycling company u

$$\begin{aligned}\max\ &\sum_{u\in U}\sum_{i\in I}\sum_{q\in Q}(e^{A}_{i}-c^{Q}_{iqu})\times y^{Q}_{iuq}\\ &+\sum_{u\in U}\sum_{i\in I}\sum_{u'\in U:u'\neq u}(-c^{U}_{iuu'})\times y^{U}_{iuu'}\\ &+\sum_{u\in U}\sum_{i\in I}\sum_{r\in R}(e^{V}_{ir}-c^{R}_{iur})\times y^{R}_{iur}\\ &-\sum_{u\in U}\sum_{j\in J}c^{Z}_{ju}\times x_{ju}\end{aligned} \tag{3.1}$$

$$\begin{aligned}\min\ &\sum_{u\in U}\sum_{i\in I}\sum_{q\in Q}ced^{Q}_{iqu}\times y^{Q}_{iuq}\\ &+\sum_{u\in U}\sum_{i\in I}\sum_{u\in U:u'\neq u}ced^{U}_{iuu'}\times y^{U}_{iuu'}\\ &+\sum_{u\in U}\sum_{i\in I}\sum_{r\in R}ced^{R}_{iur}\times y^{R}_{iur}\\ &+\sum_{u\in U}\sum_{j\in J}ced^{Z}_{ju})\times x_{ju}\end{aligned} \tag{3.2}$$

$$\min\sum_{u=1}^{U}(\sum_{i=1}^{I}(\sum_{q=1}^{Q}y^{Q}_{iuq}-\sum_{r=1}^{R}y^{R}_{iur}\times rec_{ir})) \tag{3.3}$$

These objectives are to be followed taking certain restrictions of the recycling system into account. First, material balances are set up for every single disassembly company of the network. The output of a treatment company (y_{iu}^{D}) is given by the net result of all inputs of appliances from sources outside the network (y_{iuq}^{Q}), the input of appliances and material fractions from other treatment companies ($y_{iuu'}$), and the transformation of masses related to treatment. The latter is expressed as the number of executions of a treatment activity (x_{ju}) multiplied with an input-output coefficient (v_{ij}) specifying the input-output relationships of products and material fractions i of this activity j.

$$(\sum_{j} x_{ju} \times v_{ij}) + \sum_{q=1}^{Q} y_{iuq}^{Q} + \sum_{u=1, u \neq u'}^{U} y_{iuu'}^{U} = y_{iu}^{D} \qquad i = 1, ..., I; u = 1, ..., U \quad (3.4)$$

According to equation 3.5, the output of a treatment company (y_{iu}^{D}) is either delivered to recovery companies or disposal sites (y_{iur}^{R}) or to other (specialized) treatment companies ($y_{iuu'}$).

$$y_{iu}^{D} = \sum_{u=1, u \neq u'}^{U} y_{iuu'}^{U} + \sum_{r=1}^{R} y_{iur}^{R}, \qquad i = 1, ..., I; u = 1, ..., U \quad (3.5)$$

In addition to these material balances, different external and internal restrictions exist. All products available at sources must be accepted and properly treated (equation 3.6). Additionally, restrictions exist regarding treatment capacities at companies (equation 3.7), which are described in maximal costs the company is able to spend because of capacity restrictions. For example, the number of employees (or working stations) available at one company times the costs for one worker for one month determines the capacity (given in costs) that is available for manual recycling. This description is chosen, since capacity depends on durability of activities performed. Additionally, capacities at recovery and disposal sites are to be regarded (equation 3.8).

$$\sum_{u=1}^{U} y_{iuq}^{Q} = y_{iq}^{QMAX}, \qquad i = 1, ..., I; q = 1, ..., Q \quad (3.6)$$

$$\sum_{j=1}^{J} c_{ju}^{z} \times x_{ju} \leq C_{u}^{ZMAX} \qquad u = 1, ..., U \tag{3.7}$$

$$\sum_{u=1}^{U} y_{iur}^{R} \leq y_{ir}^{RMAX} \qquad i = 1, ..., I \qquad r = 1, ..., R \tag{3.8}$$

Additionally, the non-negativity constraints are set (9)

$$y_{iuq}^{Q}, y_{iuu'}^{U}, x_{ju}, y_{iur}^{R}, y_{iu}^{D} \geq 0 \tag{3.9}$$

We start by developing a model for allocation of end-of-use products. Our assumptions do not limit the applicability of the model in regions where the collection points are organized by the municipality, as described. The formulation, obviously, does not change for situations in which companies are responsible for the collection. In more detail, our assumptions are

1. The collection points, recycling facilities and disposal sites are fixed. We assume the situation in which the nodes of the recovery network are fixed. This is the case in regions served with a good recovery infrastructure. The decision concerns which facilities will receive the end-of-life products.

2. The unitary recycling fees are constant. We assume that there are no economies of scale. The assumption is based on the fact that the recycling facilities process end-of-life products from another OEMs. This decreases the marginal contribution of any excess demand, since the total demand is shared among other OEMs.

3. Unitary transportation fees are constant. We assume that there are no economies of scale regarding transportation.

3.5 The solution approach

The proposed formulation for each of the objectives separately is obviously solvable in polynomial time, and therefore needs no specifically designed algorithm. For the version with multiple objectives, the required CPU-time largely varies with the number of objectives (Steuer [2003]) and with the methodology to used to elicit preferences.

The goals when solving a problem in a multi-objective setting are threefold: (i) identifying the solutions that are not dominated, (ii) capturing the decision maker preference, or elicit preference and (iii) aiding on the decision regarding the "best" or preferred solution.

For item (i), the endeavor is purely mathematical, and for this particular problem, trivial. ϵ-constraint methods, weighted sum optimization, lexicographic optimization are examples of formulations that will yield Pareto optimal solutions in polynomial time. Fulfilling the goals presented in items (ii) and (iii) is less trivial (Roy [1990]). In fact, as the large number of different methodologies proposed to elicit such preferences suggest, the task is very complex.

In a nutshell, these methodologies are divided in three types (Evans [1984]). The classification regards the timing in which the preference is elicited. The first type of methods are those requiring a prior articulation of the preferences. The preferences may be expressed by weights concerning the relative importance of each objective function, minimum thresholds for the value of the objective functions, or nadir points, to name some. Examples of such formulations are the ϵ-constraint methods, weighted sum scalarization, and lexicographic optimization. For a description of these models see Chankong and Haimes [1983].

The second part consists of the so called interactive method, e.g. ELECTRE (Roy [1968]), STEM (Benayoun et al. [1971]), Pareto Race (Korhonen and Wallenius [1988]), and UTA (Jacquet-Lagreze and Siskos [1982]). In these methods the user interacts with the formulations. The basics steps of the interactive methods are two, which are sequentially repeated until the desired solution is reached. The steps are (i) find a (preferably) feasible solution, and (ii) interact with the DM and get a reaction from this solution (Shin and Ravindran [1991]). The algorithm stops whenever the decision maker is satisfied with the solution.

The third type of formulations advocates the characterization of the efficient frontier. The frontier can be characterized by the enumeration of its efficient vertices for MOLP. For this purpose, one of the most common methodologies is the multi-objective simplex method. For the bi-objective case, another way to characterize the efficient frontier is to approximate it (Fruhwirth et al. [1989], Liu et al. [1999], and Fernandez and Toth [2007]). The visual representation of the approximated frontier improves the decision process (Fernandez and Toth [2007]).

In Sections 3.5.1, 3.5.2, 3.5.3 we review the main literature regarding the three aforementioned methodologies.

3.5.1 Preference elicitation prior to the model

In broad terms, in non-interactive methods the decision maker elicits its preferences before the model is constructed. The preferences may be expressed by weights concerning the relative importance of each objective function, minimum thresholds for the value of the objective functions, nadir points, to name some. The following methods are widely used to find Pareto optimal solutions. A thorough description of the models are found in Ehrgott and Gandibleux [2000].

- *weighted sum scalarization.* Weighted sum scalarization is probably one of the most popular formulations in MOP. The basic idea is to give positive weights (for maximization problems) to the objective functions. For MOLP, the solution of the problem is one Pareto optimal vertex of the formulation. Once the feasible region is convex, every vertex is a candidate solution for the weighted sum scalarization. The weights will define which Pareto optimal solution will be chosen.

- *ϵ-constraint methods.* The main idea of the ϵ-constraint methods is to determine minimum thresholds for some of the objective functions. The method is probably the most used for multicriteria optimization (Ehrgott and Gandibleux [2000]). The solutions for the ϵ-constraint methods are always at least weakly-Pareto optimal, and under certain properties, Pareto optimal.

- *lexicographic optimization.* The idea behind lexicographic optimization is to rank the objective functions. One simple formulation of lexicographic optimization works as follows: The problem is optimized for the objective function of higher priority. The maximum of the objective function is used as a minimum threshold for the objective function. The second objetive function is optimized with the aforementioned objective function. The procedure follows until the last objective function is optimized.

- *Benson's method.* In the Benson's method, the idea is to start with a feasible solution and from that initial value find a Pareto optimal solution.

- *compromise solutions.* The idea of the compromise solution is to find a solution that is “close” to the ideal point in MOP. The ideal point is defined as the point in which the vector containing the maximum of each objective function. The distance is given by a chosen metric. If the metric is strictly monotone, then Pareto optimality is guaranteed.

3.5.2 Progressive articulation of the preference elicitation: the interactive methods

The interactive methods are those in which the decision maker elicits its preference via a human-machine interaction with the proposed model. The basics steps of the interactive methods are two, which are sequentially repeated until the desired solution is reached. The steps are (i) find a (preferably) feasible solution, and (ii) interact with the DM and get a reaction from this solution (Shin and Ravindran [1991]). The stopping point, where the preferred, or best-compromising solution is reached, is determined by the user.

A myriad of different interactive methods have been developed in the last thirty years. ELECTRE (Roy [1968]), STEM (Benayoun et al. [1971]), Pareto Race (Korhonen and Wallenius [1988]), UTA (Jacquet-Lagreze and Siskos [1982]) and their many variants are examples of interactive methods.

3.5.3 Preference elicitation a posteriori: characterization of the Pareto frontier

The aforementioned methods to find Pareto optimal solutions and to elicit the preference of the decision maker result in one solution that is best-compromised or preferred. An alternative approach is to describe the efficient frontier. For the bicriteria problem, the efficient frontier can be visualized, and the decision making can be facilitated. For problems with more than two objectives, visual representation is more difficult. The complete enumeration of all efficient vertices is one alternative for the characterization of the efficient frontier. The main methods in this particular realm are summarized below.

- *Enumeration of efficient vertices.* Enumerating the efficient vertices of the MOLP is a way to characterize the efficient frontier. The advantage of such approach is that there is no assumption regarding the value function. There are two disadvantages, however (Evans [1984], Steuer [1986]).

  First, the necessary computational time forbids such approach for real problems. Finding one extreme Pareto efficient point is achieved in polynomial time, but the number of efficient points can grow exponentially in the problem size, i.e. in the graph of Zadeh (Ruhe [1988]). The difficulty of finding all extreme efficient solutions is well documented in literature (see Steuer [1986], Steuer [1994],Sayin [1996], Benson and Saying [1998], Malgorzata and Zhang [1997], Benson [1998], Aurovillian and Wiecek [1998], Steuer and Piercy [2005] and Ehrgott and Gandibleaux [2007]). Research performed or funded by NASA points to the direction to parallelism as the only way to solve large scale problems (Malgorzata and Zhang [1997] and Aurovillian and Wiecek [1998]). Some results also indicate intractability concerning problems with three objectives, such as the one we are interested in (see section 3.4). A number of results for small (i.e. less than a hundred of constraints and variables) instances with problems with three objectives are found in Hwang and Masud [1979], Rakes and Reeves [1997], Strijbosch et al. [1991] and Steuer [1994], among others. To the best of our knowledge, no numerical analysis is available for the instance sizes we intend to solve, particularly for the problem with 3-objectives. Generally speaking, existing formulations are restricted to small problems and potentially to medium problems when parallelism is applied (see Aurovillian and Wiecek [1998] and Benson [1998]). The numerical results point to the intractability of the problem, even for three objectives

Second, the number of solutions is too large and it has two major implications. First, the number of solutions may become too large to store. Second, and more importantly, due to our limited capacity to compare different alternatives, it may become unpractical to compare all the efficient solutions.

- *Approximation of the efficient frontier* The approximation methods, as the name suggests, approximate the efficient frontier via a second frontier that is close to the original one. Fruhwirth et al. [1989], Liu et al. [1999], Fernandez and Toth [2007] are examples of such approach for problems with three objectives.

3.6 Which methodology to use?

In the previous section we reviewed the main methodologies in MOLP. In this section we advocate the usage of a characterization of the efficient frontier for the problem we intend to solve. More specifically, we intend to characterize the Pareto efficient frontier. Our decision is based on the following:

- Evaluation of the current situation in terms of the system's efficiency relative to environmental impact and costs. It is possible, for instance, to calculate efficiency indices for existing network configurations using DEA techniques. For further description of DEA see the seminal paper of Charnes et al. [1978].
- Determination of the trade-offs between the resulting environmental impact and costs in a logistics network.

The Pareto optimal frontier is composed of the set of the images of all efficient solutions for the network regarding two objectives: optimize economic and environmental goals, like cost minimization and waste minimization, respectively. A multiobjective program is denoted by (Steuer and Piercy [2005]):

$$\max\{c^1 x = z_1\}...max\{c^k x = z_k\} \quad s.t. \quad \{x \in \mathbb{R}^n \mid Ax \leq b, b \in \mathbb{R}^m, x \geq 0\} \quad (3.10)$$

where k is the number of objectives. A point $\hat{x} \in S \subset \mathbb{R}^n$ is *efficient* if and only if there is no $x \in S$ such that $c^i x \geq c^i \hat{x}$ and there is at least one $c^i x < c^i \hat{x}$. The *efficient set* or *efficient frontier* is the set of all efficient solutions. In our formulation, $c^1 x$ represents the CED, $c^2 x$ represents waste and $c^3 x$ the costs.

For small instances of the problem described in section 3.4, one way to characterize the efficient frontier is to enumerate all efficient vertices, as described in 3.5.3. In general, for problems with a couple hundreds of variables and constraints, it is possible to enumerate all efficient vertices (Wallenius et al. [2008]).

For large instances (i.e. problems with thousands of variables), however, literature suggests that such approach is impossible, as discussed in section 3.5.3. The formulation proposed in section 3.4 has a couple thousands of variables and constraints and such enumeration is, therefore, not possible. For this reason, we propose in the next chapter a simple algorithm to deal with such computational intractability.

3.7 Evaluating eco-efficiency in recycling networks

In sections 3.4 and 3.5 we presented a formulation for the design of eco-efficient recovery networks. In this section, we propose a simple method to evaluate the efficiency of existing networks.

Intuitively, we can think of the efficient solutions explored in the last section as benchmarks for existing logistics networks. Comparing the mapped environmental impact and costs of the current configuration to the theoretical optimal provides an indicator of efficiency in existing logistics network. If the actual environmental impact and costs are close to the frontier, for instance, there will be no need for configuration changes. Furthermore, it is possible to give a measure of efficiency for existing networks. In order to provide a efficiency measure of a given existing recovery network, we need the following lemmas:

Lemma 3.1. *Each image of a non-dominated $\hat{x}$ solution in equation 3.10 $(c^1\hat{x}, ..., c^k\hat{x})$ is an efficient* Decision Making Unit *(DMU) in a CCR DEA problem with DMU's $(c^1\hat{x}^1, ..., c^k\hat{x}^k)$ for $x \in S \subset \mathbb{R}^n$ in equation 3.10.*
Proof: *For a problem with a continuous set of images of non-dominated solutions, the linear convex combinations of these images also map a real solution in the original problem. In that case, since the convex combinations are part of the images of the solution set for the problem at question, the posterior addition of such solutions will not dominate any previously existing non-dominated solution. As no convex combination will result in a solution that dominates the original non-dominated set, the efficient solutions will map efficient DMUs in a DEA problem.*

Lemma 3.2. ***E**very non-dominated $\hat{x}$ solution in (1) $(c^1\hat{x}^1, ..., c^k\hat{x}^k)$ is an efficient Decision Making Unit (DMU) in a CCR DEA problem with DMU's $(c^1\hat{x}^1, ..., c^k\hat{x}^k)$ for $x \in S \subset \mathbb{R}^n$ in (1), in case we require $x \in S \subset \mathbb{Z}^n$, iff $\hat{x}$ is also supported*
Proof: *For non-supported solutions, there exists at least two supported solutions that makes the non-supported solution inefficient in DEA terms. For supported solutions, no convex combination of other supported solutions dominates it.*

For an in-depth discussion of such properties of DEA and MOP, see Korhonen et al. [2003]. For equivalences between efficient solutions in the particular problem of multi-objective resource allocation problem see Yougbaré and Teghem [2007].

We first formalize our approach, for linear models (allocation models). We map every image of the non-dominated solutions as an efficient DMU of a DEA formulation, using Lemma 3.1. Since the problem is linear, all efficient solutions are supported, and are, therefore, efficient in DEA terms (the same does not hold with combinatorial or mixed-integer problems). After this step, we calculate efficiency based on the efficiency measure proposed by Cooper et al. [1999]. We use the projection of Cooper et al. [1999] due to the fact that it provides a more robust measure if compared to the traditional radial projection as proposed by Charnes et al. [1978]. The projection we use avoids projections in Pareto inefficient parts of the frontier, providing a measure that assess the inefficiency of all dimensions within the analysis (in our case environmental impact and logistics network costs).

It is also possible to explore other projections for such problems, allowing the decision maker to more freely explore the efficient frontier. In other words, it is possible to explore solutions in which the increase in profits, or the decrease in cumulative energy demand, or waste is not done in an equiproportional way. For interactive and non-articulated methods for finding radial projections see Golany [1988], Thanassoulis and Dyson [1992], Zhu [1996], Halme et al. [1999], and Korhonen [2003]. Furthermore, it is easy to see that the equivalence works from the DEA formulation to the multi-objective one: every non-radial projection in the DEA formulation maps a real solution in the original logistics network. Figure 3.7 illustrates the efficient frontier and the current values of environmental footprint and costs.

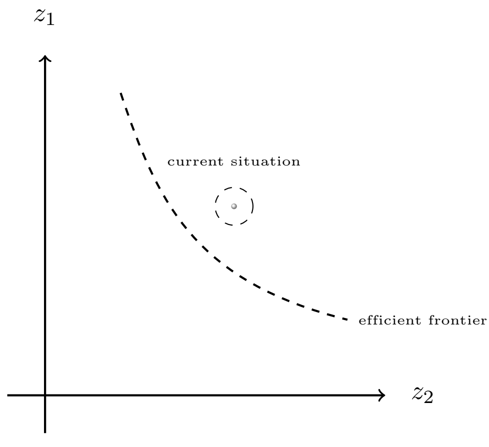

Figure 3.7: Efficient frontier and current value of environmental footprint and costs

The advantages of using this approach is that the entire literature from projections in DEA can be directly applied. Efficiency measurement is in the heart of DEA, and researchers have been working for almost thirty years on efficiency measures, since the seminal papers of Charnes et al. [1978]. The disadvantage is that the approach requires that all efficient solutions are found. As presented in the previous section, this task can be computationally untractable for the instances we are interested in. A second approach is to calculate the efficiency of the existing solution directly using MOP. The computational advantage is clear: for some models a projection point can be found in polynomial time. The disadvantage is that efficiency measurement in MOP is a novelty, if compared to the efficiency measurement in DEA. Examples of such approach are found in Ehrgott and Gandibleaux [2007].

3.8 Conclusions

The concern of consumers, companies and governments with the environment has steadily increased in the last years. Cleaner processes, reuse of products and components, remanufacturing and recycling are examples of initiatives to reduce the environmental impact of logistic networks. Unfortunately, win-win solutions for the environment and business are very elusive in practice.

The adoption of cleaner solutions is generally bound by an increase in costs. Companies aiming to decrease the environmental impact of their logistic networks should, then, look for good trade-offs between environmental impact and costs. The game is, therefore, smartly compromising the two P's: *Planet* and *Profit*. The same rationale is true for governments: effective legislation should take into consideration specific trade-offs of the logistic network in question, as well as the efficiency of the existing logistic network.

In this chapter we present a framework for optimizing the design of efficient logistic networks, based on MOP, in terms of the environment and costs. We also discuss the expected computational challenges of such approach for the design of recovery sustainable logistic networks. Applications and further developments of such frontier are also discussed.

In addition, we introduce a new methodology to evaluate efficiency in logistic networks, based on the properties shared by MOP and DEA. We also point out the main mathematical characteristics of such an efficiency indicator. The indicator tells the decision maker, in companies, sectors or governments, about the necessity of better coordinating his logistic networks, or better tuning environmental legislation.

Chapter 4

A methodology for assessing eco-efficiency in recycling networks

4.1 Introduction

As presented in the previous chapter, considerable reductions in the environmental footprint of many activities, including in reverse logistics, are not free. The win-win solutions for business and the environment seem quite elusive in practice, in particular for considerable reductions in environmental impacts (Walley and Whitehead [1994]). The popular saying "there is no such a thing as a free lunch" could not be more true in this case. In the sphere of the "no free lunch" paradigm, some questions should be posed: How much do we have to spend in order to improve environmental quality? Or in more scientific terms, which trade-offs occur between the environmental impacts of an economic activity and its costs? And, what are "best" solutions balancing ecological and economic concerns? (Quariguasi Frota Neto et al. [2008]). In the normative and qualitative field, these questions have led to the concept of trade-offs and efficient frontiers for business and the environment (Huppes and Ishikawa [2005]). The rationale is to determine the set of solutions for which it is not possible to decrease environmental damage, or to increase total environmental quality of each environmental category, without increasing costs. These solutions are called *eco-efficient*, as discussed in the previous chapter. Figure 4.1 illustrates the efficient frontier and the trade-offs. The axes represent the indices of the economic value and the environmental quality of an economic activity. The curve represents the efficient frontier, where one cannot either decrease the environmental pressure without decreasing the economic value added or reduce the costs without increasing the environmental footprint (Kuosmanen and Kortelainen [2005]). The area below the curve is not eco-efficient: it is feasible to increase economic value without restricting environmental quality or the other way round. We assume that the actual situation represents an inefficient solution. This solution can be improved by moving to the efficient frontier. As each point on the efficient frontier is Pareto optimal, it is up to the decision maker which improvement path is preferable. Increasing environmental quality without losing economic value means moving to the right, increasing economic value without losing environmental quality means moving up. The trade-off line is chosen by society.

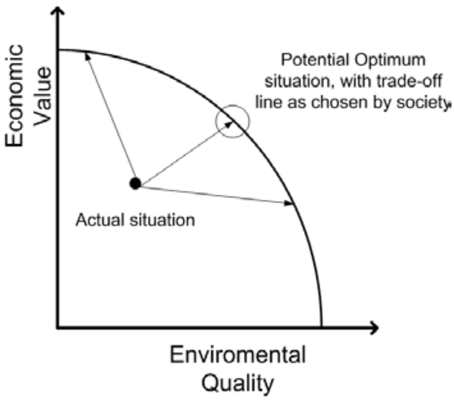

Figure 4.1: Eco-efficiency in society: Actual technologies and production possibility envelope. Adapted from Huppes and Ishikawa [2005].

From a methodological perspective, determining such an efficient frontier or assessing the trade-offs in the context of recovery networks is quite new, despite the extensive existing literature in the field of MOP. In the previous chapter, we formulated the recovery network problems and suggested the usage of weigh-sum scalarization to explore the efficient frontier concerning costs, waste and CED minimization. We have also suggested that the complete exploration of the efficient vertexes is intractable regarding CPU-time. In this chapter we propose a different methodology. We propose a methodology that capitalize at one of the decision maker's most effective cognitive

capabilities: visual representation. In order to explore the efficient frontier in feasible CPU-time and in order to present a good visual representation of the frontier, we develop a very simple two-phase heuristic. In the first phase, the algorithm determines, for a number of network configurations with the same cost, efficient points of the bi-objective frontier regarding CED and waste. The heuristic tries to obtain equally dispersed points within the frontier. The first phase belongs to the class of methods in Multiple Criteria Decision Making (MCDM) called ϵ-constraint methods. In the second phase, the user selects his preferred solution from the ones provided by phase one. The algorithm then projects this solution into the efficient frontier of the problem with three objectives. The proposed approach can be used by companies to redesign their supply chains in order to balance their environmental footprint and the life cycle costs of their products. This approach can also be used by governments to evaluate the effectiveness of environmental regulations.
The chapter is organized as follows: Section 4.2 presents our methodology, the *eco-topology*. We focus on the users' interaction in our approach, although the computational results are at least as interesting. Section 4.3 highlights the comparison between the existing methods and the one we propose. We clearly show the advantages of the latter. In Section 4.4 we illustrate our method, applying it to the recovery network described in the last chapter. Section 4.5 presents the conclusions.

4.2 Exploring eco-efficient solutions, the concept of eco-topology

In Chapter 3, we describe the first approach to define the theoretical frontier of Huppes and Ishikawa [2005] concerning recycling networks. A cradle-to-grave approach is used to determine the eco-efficient frontier regarding business and the environment for the design of sustainable logistics networks. As presented in Chapter 3, the diverse phases of a product (raw material extraction, manufacturing, transportation, use and end-of-use alternatives) are taken into account to determine the optimal solutions.

Solving the MOLP problem, or finding every extreme efficient solution has two major drawbacks. The first concerns CPU-time, as discussed in chapter 3. We overcame this problem by interactively exploring points on the frontier via weighted sum methodologies[1]. The drawback of such a formulation is well-known in the MCDM literature: complete regions of the frontier may stay completely unexplored. This approach does not ensure the number of efficient solutions found or the distance between them. The second drawback regards the visualization and interpretation of results. Dividing the environmental impact to three or more subcategories would lead us to a frontier which, besides being very difficult to completely define, is not easy to visualize.

Another way to overcome the intractability of finding all extreme efficient solutions is to look for approximations of the frontier. For the bi-objective multiobjective problem, Fruhwirth et al. [1989], Liu et al. [1999], Bernd et al. [2001] propose approximations for the non-dominated frontier. To the best of our knowledge, however, no approximation has been proposed for non-dominated frontier of dimensions higher than two.

In order to overcome the two aforementioned problems, CPU-time intractability and visual representation, we propose a very simple heuristic to explore the non-dominated efficient frontier. We call this method *eco-topology*. In the first phase of the model, we generate a number of non-dominated frontiers for the biobjective problem regarding the minimization of CED and waste. We call them *iso-cost* curves. In the second phase, the user defines his preferred non-dominated point, and the algorithm projects such point on the efficient frontier regarding the three objective functions. The first phase of the heuristic belongs to a class of MCDM methods called ϵ-constraint methods. A formalization and explanation of the method can be found in Ehrgott and Gandibleux [2000]. The idea of the method is to provide weakly efficient solutions or efficient solutions by transforming all but one objective function in constraints. The second phase can be classified as a weighted sum method.

The term eco-topology designates a set of piecewise linear frontiers, which we call *iso-cost*, in which it is possible to change trade-offs between environmental impact classes, i.e. CED and waste, while maintaining the same costs. The objective in this formulation is to provide the decision maker with the flexibility to determine his preferred target without the use of interactive processes or weight setting. The algorithm performs in $O((\frac{1}{\epsilon})^2 \times n^6)$, for our example with three objective functions.

[1]The equivalence between a weighted single objective LP and a multi-objective one defined in the same feasible polyhedron is a well-known result in MOP. Let $\Lambda = \{\lambda \mid \lambda_i \in E^k, \sum_{i=1}^{k} \lambda_i = 1\}, \quad i = 1, ..., k$ and the LP problem be defined as the $Max_{x \in X} \sum_{i=1}^{k} \lambda_i \cdot f_i(x)$ subjected to $x \in X$. Defining $X^\star(\lambda)$ as the subset of $x \in X$ that maximizes the function $\lambda f(x)$, we have that $U_{\lambda>0} X^\star(\lambda) \in X_n \in U_{\lambda \geq 0} X^\star(\lambda)$ (Zeleny [1974])

The term $\frac{1}{\epsilon}$ represents the number of different values of the first and second objective function we intend to use as constraints in order to assess the third objective function. The number of linear problems we solve, is therefore equal to $\frac{1}{\epsilon}^2$, since we have one nested loop of size $\frac{1}{\epsilon}$ within a loop of the same size. For this formulation, therefore, computational time grows in polynomial time. It is easy to see, however, that the problem grows exponentially with the number of objective functions.

In the next section we present the algorithm for three objectives and the necessary lemmas.

Algorithm for a 3-objectives case:
Suppose the decision maker wants to maximize the revenue of a reverse logistics network (z_1), and minimize two environmental impacts (z_2 and z_3), e.g. cumulative energy demand and landfilled waste. In this case, the first phase of the heuristic is as follows:

1. Calculate the $max\{z_1\}$, $min\{z_2\}$, $min\{z_3\}$ and check the existence of $z_1 = 0$
2. For $i = 1$ to $\frac{1}{\epsilon}$ do
   $\hat{z}_1 = max\{z_1\} \cdot \epsilon \cdot i$
   $\dot{z}_2 = min\{z_2 \mid z_1 = \hat{z}_1\}$ and $\dot{z}_3 = min\{z_3 \mid z_1 = \hat{z}_1\}$,
   $\ddot{z}_2 = min\{z_2 \mid z_1 = \hat{z_1} \ \wedge \ z_3 = \dot{z}_3\}$
   $\ddot{z}_3 = min\{z_3 \mid z_1 = \hat{z_1} \ \wedge \ z_2 = \dot{z}_2\}$
   3. For $j = 1$ to $\frac{1}{\epsilon}$ do
      $\hat{z}_2 = \dot{z}_2 + (\ddot{z}_2 - \dot{z}_2) \cdot \epsilon \cdot j$
      $\hat{z}_3 = \{min\ z_3 \mid z_1 = \hat{z_1} \ \wedge \ z_2 \leq \hat{z_2}\}$
      $F \leftarrow (\hat{z}_1, \hat{z}_2, \hat{z}_3)$
   end do
end do
4. Connect pairwise the $f \in F$ with the same profit
5. end

where:
z_1 is the first objective function: marginal revenue of the network
z_2 is the second objective function: cumulative energy demand,
z_3 is the third objective function: landfilled waste,
ϵ is an auxiliary variable: the smaller this variable; the higher the number of points on the frontier that are explored, and therefore the better the representation of the frontier.

F is the set of solutions for our formulation. It is easy to see that at least one solution exists for each $\hat{z}_3 = \{min\ z_3 \mid z_1 = \hat{z_1}\ \wedge\ z_2 \leq \hat{z_2}\}$, and that this solution is Pareto optimal for the biobjective case. We first prove the following lemmas:

Lemma 4.1. *If $max\{z_1\}$, $min\{z_2\}$, $min\{z_3\}$,$z_1 = 0$ exists, then $\hat{z}_1$, $\dot{z}_2$,$\ddot{z}_2$, $\dot{z}_3$ exist.*

Proof. Let $S \subset \mathbb{R}^n$ and $f : S \rightarrow \mathbb{R}^k$, it is a well known fact that if S is convex and f is linear, the image of S under f is also convex. It implies that $f :\rightarrow \mathbb{R}^k$ is also connected. Since $max\{z_1\}$ is limited and $z_1 = 0$ exists, any solution $\hat{z}_1 = max\{z_1\} \cdot \epsilon$ exists for $0 \leq \epsilon \leq 1$. Once $\hat{z}_1$ and $min\{z_2\}$ exist, $\dot{z}_2$ exists. The Proof for $\dot{z}_3$, $\ddot{z}_2$, $\ddot{z}_3$ is analogous. □

Lemma 4.2. *If $min\{z_2\}$ and $min\{z_3\}$ exist, all efficient solutions of the original problem with the constraint $z_1 = \hat{z_1}$ are linear combinations of $(\hat{z}_1, \dot{z}_2, 0)$, $(\hat{z}_1, 0, \dot{z}_3)$,$(\hat{z}_1, \dot{z}_2, \ddot{z}_3)$ and $(\hat{z}_1, \ddot{z}_2, \dot{z}_3)$.*

Proof. Any solution $(\hat{z}_1, \mathring{z}_2, \mathring{z}_3)$ given $\mathring{z}_2 < min\{z_2\}$ is unfeasible. The same rationale is valid for $\mathring{z}_3 < min\{z_3\}$. All solutions $(\hat{z}_1, \mathring{z}_2, \mathring{z}_3)$ given $\mathring{z}_2 > \dot{z}_2\ \wedge\ \mathring{z}_3 \geq \ddot{z}_3$ and $\mathring{z}_2 \geq \dot{z}_2\ \wedge\ \mathring{z}_3 > \ddot{z}_3$ are non Pareto optimal. The same rationale is valid for $\mathring{z}_3 > \dot{z}_3\ \wedge\ \mathring{z}_2 \geq \ddot{z}_2$ and $\mathring{z}_3 \geq \dot{z}_3\ \wedge\ \mathring{z}_2 > \ddot{z}_2$. The remaining solutions are enclosed in a square with vertexes $(\hat{z}_1, \dot{z}_2, 0)$, $(\hat{z}_1, 0, \dot{z}_3)$, $(\hat{z}_1, \dot{z}_2, \ddot{z}_3)$ and $(\hat{z}_1, \ddot{z}_2, \dot{z}_3)$. □

Directly from Lemma 1, we can always find a solution $f = (max\{z_1\} \cdot \epsilon \cdot i, \mathring{z}_2, \mathring{z}_3)$. If $min\{z_2\}$ and $min\{z_3\}$ are bounded, there is a solution for $\dot{z}_2$ and $\dot{z}_3$. Using Lemma 2, and the fact that all extreme efficient solutions are connected ($(\hat{z}_1, \dot{z}_2, \ddot{z}_3)$ and $(\hat{z}_1, \ddot{z}_2, \dot{z}_3)$ are also Pareto optimal), there is a path from $\dot{z}_2$ to $\dot{z}_3$ that can be expressed as the linear combination of $(\hat{z}_1, \dot{z}_2, 0)$, $(\hat{z}_1, 0, \dot{z}_3)$, $(\hat{z}_1, \dot{z}_2, \ddot{z}_3)$ and $(\hat{z}_1, \ddot{z}_2, \dot{z}_3)$. Therefore for any $\hat{z}_2 = \dot{z}_2 + (\ddot{z}_2 - \dot{z}_2) \cdot \epsilon \cdot j$ there will be one and only one Pareto optimal point (not necessarily a vertex) $(\hat{z_1}, \hat{z}_2, z_3)$. Since $\hat{z_1}$ and $\hat{z_2}$ are constants, this point is $\hat{z}_3 = \{min\ z_3 \mid z_1 = \hat{z_1}\ \wedge\ z_2 = \hat{z_2}\}$

The problem with the added constraint is an ϵ-constraint method, with the particularity that for the respective LP, feasibility is guaranteed. Ehrgott and Gandibleux [2000] prove that for any closed solution space, the solution for the ϵ-constraint, if existent, is al least weakly efficient. For the bicriteria linear problem, it is easy to see that the solutions generated in the inner loop of the heuristic are efficient, but not necessarily extreme. The figure 4.2 illustrates the first phase of the algorithm.

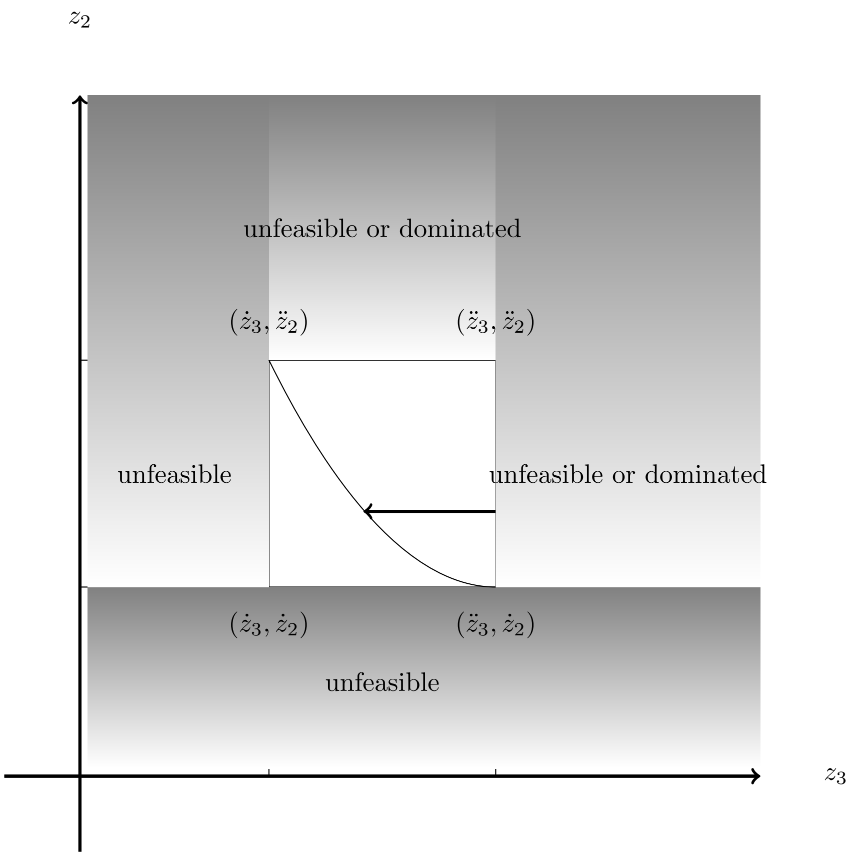

Figure 4.2: The proposed search for equally dispersed Pareto efficient solutions

The solutions F are not necessarily Pareto optimal with respect to the original MOLP problem, due the constraint $z_1 = \hat{z_1}$, but they are Pareto optimal for the original problem plus constraint $z_1 = \hat{z_1}$. In our case study (Section 4.4) we test efficiency "a posteriori". The next phase of our procedure works as follows. First, the user differentiates, in the graphical representation, the Pareto optimal from the non Pareto optimal solutions. This process could be also performed "a priori", cleaning the solutions that are dominated by some other solution in the graph. We believe, however, that leaving such solutions gives the decision maker a better "intuition" of the topology of feasible solutions. Second, the user decides on his preferred solution. Third, an algorithm finds an efficient solution by, in this order, increasing profitability and decreasing CED and generated waste. The procedure works aforementioned algorithm works as follows:

1. normalize the objective functions.
2. with the preferred solution (z_1^p, z_2^p, z_3^p) $max\{\lambda_1 \cdot z_1 + \lambda_2 \cdot \{z_2 + z_3\}\}$ s.t. $Ax \leq b$,$z_1 \leq z_1^p, z_2 \leq z_2^p, z_3 \leq z_3^p$ and $\lambda_1 \gg \lambda_2, \lambda_3$

It is easy to see that the final solution is Pareto optimal.

4.3 Comparison between eco-topology and the existing methods

We compare the eco-topology methodology with the three methodologies presented in section 2: 1) single ratio methods, 2) preference structure methods based on weighting and 3) multi-objective methods based on the complete exploration of the extreme efficient vertices. We also draw parallels between the different methodologies.
The single ratio methodology proposes a single efficiency measure to select one solution out of a set of solutions, according to the highest $\frac{Economic\ Value}{Environmental\ Pressure}$ ratio. The main drawbacks of such formulation are:

- it is not possible to differentiate between different environmental impacts or to add new variables to the model, such as social aspects or performance levels.
- it does not give any information on the theoretical trade-offs between the dimensions of analysis (in our case business and planet).
- The decision maker has no flexibility to choose targets according to his preferred solution. A high rate could, for example, be possible only via a cheap and environmentally unfriendly process; or alternatively, an extremely environmental friendly process with extremely high costs. Both could be undesirable, if not unrealistic.

In mathematical terms, the ratio procedure is nothing but a DEA model with two variables and constant returns of scale. It can only be applied to a discrete set of alternatives. The eco-topology approach allows the decision maker to freely decide on the best trade-offs or location on the optimal frontier. It also allows an increment on the number of objectives, allowing discrimination between the different environmental pressure classes and the insertion of new variables, such as performance levels. The trade-offs between these variables can be determined and easily visualized via the iso-cost curves. In the case of discrete solutions, the model should be adjusted for DEA formulations.

The Preference Structure methodology, partial exploration, is equivalent to an interactive version of the eco-curves. It is a heuristic approach as it provides a subset of solutions. First, it only explores the efficient vertices, not the corresponding hyperplanes. Second, it is not possible to ensure that all extreme points are explored. The number of alternatives is then diminished. The weighting procedure is another drawback, since the weights may not correspond to their implicit importance. A weight of 70% for the environment does not necessarily mean a solution which takes the environment for 70% into account, contrary to common belief. Furthermore, it is also not possible to determine any trade-off between different dimensions.

The multi-objective methodology is the one most closely related to the concept of eco-topology. Here, the objective is to completely explore the set of all efficient extreme solutions. This formulation gives the DM a set (in general with exponential size) of efficient solutions. In this case flexibility is given to the decision maker to decide between a given number of alternatives. There is one serious drawback: it cannot be applied to big instances. An increase in the number of variables, therefore, may turn the problem unsolvable from a CPU-time perspective. The eco-topology runs in polynomial time, at least within a constant number of objective functions. The main drawback of the proposed method is the computational complexity as compared to the Preference Structure methodology.

The models referred and presented in this paper, however, clearly do not exhaust the application of MCDM methodologies in the field of eco-efficiency. Literature in this stream of research is extremely rich, and a number of other methods are suitable for the exploration of the eco-efficient frontier. So far we have not mentioned, for instance, a number of articulated approaches. In the articulated methods the Decision Maker interacts with the model until he finds a satisfying solution. An example of such approach is the Pareto Race, or STEM , which promotes a “walk” on the facets of the frontier (Korhonen et al. [2003]). The Pareto Race enables a decision maker to freely search any part of the efficient frontier by controlling the speed and direction of motion. The values of the objective functions are presented during the Race as bar graphs on a display. For discrete problems, multi-attribute methods may also be used. We have found no literature on the application of articulated methods for eco-efficiency analysis, but it seems to be another fruitful area of research.

4.4 The German waste electrical and electronic (WEEE) case

In the following section, the algorithm described in Section 4.2 is applied to the recovery network design presented in Chapter 3. The recovery network design, as discussed in the previous chapter, is based on a real-world case study regarding the implementation of the Directive for recycling waste electrical and electronic equipment (WEEE-directive). It is the aim of this part of the paper to show the applicability of the ecotopology method, and to demonstrate how the method helps in the decision making process by visualization of efficient alternatives and calculation of trade-offs.

The data used in the calculations have been extracted from Walther and Spengler [2005], Spengler and Walther [2005] and Walther and Spengler [2004]. The authors have shared their primary data to be used in this chapter.

4.4.1 Application of the algorithm

In the following, the algorithm of Section 4.2 is applied to the WEEE case study. With regard to the given objectives, it is the overall aim to calculate the optimal allocation and treatment processes within a given infrastructure with regard to the requirements of the WEEE-directive following economic as well as ecological goals. Since we want to calculate efficient allocations based on decisions about masses (kg), the solution space is continuous. As stated in Section 4.2, it is not our intention to determine one preferred solution (as would be done by a-priory weighting of the different goals of the decision makers), but to visualize all efficient solutions and trade-offs between the different goals. Since we have three objectives, it is a three-dimensional efficient frontier, but we want to present it as two-dimensional trade-offs on iso-cost curves (thus, keeping the contribution margin constant for every curve). Based on the visualization of the efficient frontier and the trade-offs, a discussion process can start which of the solutions to choose (subjective part). We do not want to replace this discussion, but rather help in the decision making process by a presentation and visualization of all alternatives and trade-offs to the decision makers (objective part). The application of the algorithm is done for a sample region, the federal state of Lower Saxony in Germany. Actors, activities and material flows were determined within an empirical study, performed by Walther and Spengler [2005]. As a result of this analysis, 47 public waste collection points, 46 disassembly and mechanical processing companies, and 56 recycling and disposal sites with their location, specialization as well as treatment capacities were determined. Since electronic products are very heterogeneous, seven reference products resembling the average of several products were defined according to product similarities based on empirical data. Four to six disassembly depths and mechanical processing activities with corresponding quality and quantity of materials fractions were determined for every reference product. The resulting optimization problem consists of approximately 71.000 linear variables and 11.000 conditions. For the single objective case, the problem can be solved using common solution procedures for linear optimization problems in few seconds.

When applying the algorithm the profit is first maximizing ignoring all other objectives. In the WEEE case, the maximum attainable profit is 1.1 Mio €/y if CED and waste are not taken into account. This solution would be the result of a single (economic) objective optimization model, and would be chosen by a decision maker following purely economic targets. A certain number of isopretium curves is then calculated by multiplying the maximum profit with coefficients $\epsilon \cdot i$ for all $i = 1, ..., \frac{1}{\epsilon}$. Thus, each isopretium is representing a certain fraction of the maximum profit. In the WEEE case, 10 isopretium curves are calculated ($\epsilon = 0.1$), which means that the lowest profit isopretium curve (110,000 €/y) is representing 1/10th of maximum profit. For each of these ten fractions of the maximum profit, CED (objective 2) as well as waste (objective 3) are minimized separately. Doing so, the solution space is limited since unfeasible solutions (i.e. all results representing less then the minimum attainable CED and waste) can be eliminated for each isopretium curve. In the WEEE case for example, it is not possible to reach less than 5,700 GJ/y CED and 2,380 t/y of waste if a profit of 220,000 €/y is at least aimed at. Thus, if at least 220,000 €/y must be reached, the given input amount of WEEE that is collected can not be processed generating less than 5,700 GJ/y CED and 2,380 t/y waste. Keeping the profit as well as the minimal attainable CED unaltered, the minimal waste is now calculated. For a profit of 220,000 €/y and 5,700 GJ/y of CED this results in 5,830 t/y of waste . The same is done keeping the objective value of the profit as well as the minimal waste unchanged, which is for the example a profit of 220,000 €/y and waste of 2,380 t/y resulting in 8,940 GJ/y of CED. Note that there is a trade-off between CED and waste minimization in the WEEE case. Therefore, the minimization of CED and the minimization of waste each lead to maximum values for the other objective for a given profit. Applying these calculations, the solution space is bounded, and the starting and ending points of the isopretium curve are now known. Thus, the curve connecting these two points can be calculated. This is done by slowly raising the CED by a certain fraction $\epsilon \cdot i$ for all $i = 1, ..., \frac{1}{\epsilon}$, and each time calculating the minimized waste for this combination of maximized profit/minimized CED until the maximum CED (and thus in the WEEE case the minimum waste) is reached for this isopretium. The results are stored, and the algorithm is repeated by slowly raising the profit objective by $110,000$ €/y ($\epsilon \cdot$ maximum profit) until the maximum profit is reached.

4.4.2 Results

Results are shown within figure 4.3. In this figure, direct trade-offs between CED and waste are given on every iso-cost curve. However, trade-offs between profit and CED (respectively profit and waste) can also be deduced when changing from one iso-cost curve to another if the other ecological impact is kept constant. For our case study, the solution space is continuous. Thus, every point on the iso-cost curve belongs to one or several solutions with a certain characteristic of decision variables. For instance, to a certain combination of CED, waste and profit belongs a certain amount of products that is delivered from collection point q to treatment company u, where a certain number of disassembly activities is applied and as result certain material fractions i are generated that are then sent to recycling facility r. Since there are millions of possible (and even efficient) solutions, we will not focus on the solution itself, but rather on the efficient frontier and the trade-offs. A more sophisticated analysis of different solutions is given in Walther and Spengler [2005].

The results of the iso-cost curves are represented in figure 4.3. The curve ending on the right of the others represents the iso-cost for a profit of 90% of the maximum profit, or $990,000$€/y. The one ending on the left of all other represents the iso-curve for a profit of 20% the maximum profit, $220,000$ €/y. The curves in between represent, respectively 30%, 40%, 50%, 60%,70% and 80% of the maximum profit. The maximum profit (100%) has a single point (5,488 t/y and 5,892 GJ/y).

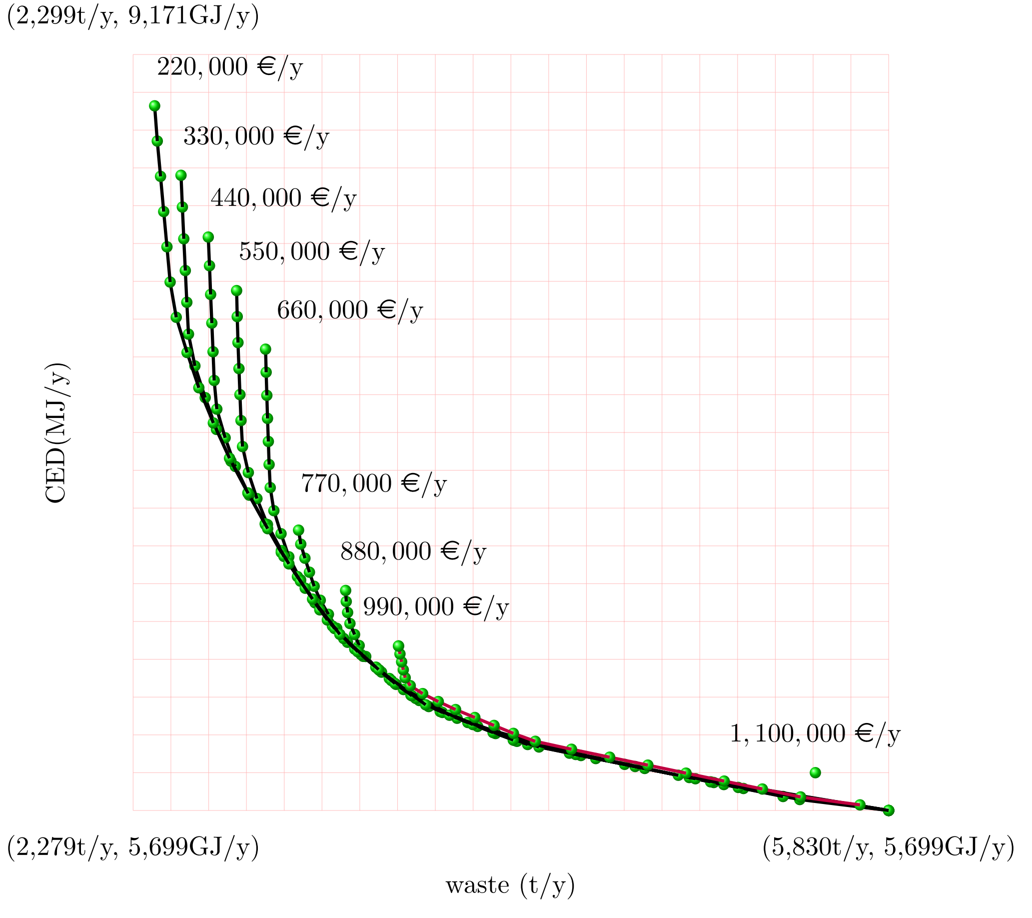

Figure 4.3: Eco-efficient frontier. The pairs (a,b) are, respectively, the landfilled waste and CED. The number at the end of the lines are profit for the isopretiums.

Looking at the iso-cost curves, it can be observed that decreasing landfill is only possible via increasing in the CED. Our results show that there is very little room for trade-off between the two environmental indicators, and the profit of the reverse supply chain. In other words, selecting less profitable supply chains do not render improvements in both environmental indicators. The reason seems to be the energy spent with transportation: the electrical and electronic equipment being diverted from landfill to other end-of-use alternatives (i.e. recycling) results in higher transportation efforts. Two facts help to explain this phenomenon. First, the fact that landfills are usually more abundant than recycling facilities, and therefore, in average close to the consumer centers helps to explain the inverse correlation of transportation (and therefore CED) and amount of end-of-life electronic ending at landfills. As land-filled waste decreases, therefore, CED increases. Second, the level of reduction on land-filling due to other end-of-life activities (i.e. recycling) are different for the different end-of-life facilities. In order to get a higher recycling percentage the equipment may have to travel longer distances.

Another interesting result is that the reduction in waste due to an unitary increase in CED rapidly deteriorates with the increase in CED. This particular result holds for all iso-cost curves. At a $220,000$ Mio €/y profit, and a CED of $5,700$ GJ/y, an increase of one MJ reduces 6.11 kg of waste landfilled. For the same unitary reduction, and a CED of $8,770$ GJ/y, the reduction is only 0.08 kg. For this particular iso-cost curve, the "shadow price" of waste per unit in kilograms per CED in GJ changes 7600% from the highest to the lowest CED levels. The results are robust for the other iso-cost curves. For the iso-cost curve of $330,000$ €/y, $440,000$ €/y, $550,000$ €/y, $660,000$ €/y, $770,000$ €/y, $880,000$ €/y we have changes in the "shadow prices" of waste (in kg) per CED (in MJ), respectively, from 6.23 kg/MJ to 0.04 kg/MJ, 6.35 kg/MJ to 0.04 kg/MJ, 6.49 kg/MJ to 0.04 kg/MJ, 6.67 kg/MJ to 0.03 kg/MJ, 7.71 kg/MJ to 0.16 kg/MJ, 8.25 kg/MJ to 0.06 kg/MJ.

Also worth noticing is the fact that the reduction in the amount of waste going to landfill due to a decrease in the profitability of the supply chain is not much affected by the level of profitability or CED. For a cost of $660,000$ €/y and a CED of $7,820$ GJ/y, a reduction in landfilling costs is approximately 1 €/kg, maintaining the level of CED. In the same iso-cost, and a CED of $7,180$ GJ/y, the reduction in landfilling costs is approximately 1.3 €/kg. The result is robust for all iso-costs. For a profit of $330,000$ €/y and a CED of $8,620$ GJ/y the reduction in landfilling is 1.4 €/kg. The cost for reduction in landfill is 2 €/kg for a $8,620$ GJ/y CED . The values are quite high compared to normal take-back prices. A 12kg computer would cost between 12€to 20€.

Looking at the results for shadow-price of CED, one can note that they rapidly increase with the increase in profitability. From iso-cost with profit of $330,000$ €/y to iso-cost with profit of $220,000$ €/y at a $8,620$ GJ/y CED, the unitary reduction costs 0.12 €/MJ. The same reduction from iso-cost with profit of $880,000$ €/y to $770,000$ €/y results in unitary cost of 0.46 €/MJ for a $6,710$ GJ/y CED. Both results seem quite high: buying the comparative amount of carbon credit would cost 0.003 €/MJ (CarbonFund [2006]).

Comparing these different iso-cost curves, one can infer that minimizing land-filled waste can only be achieved if a low profit is taken into account, or if transportation (and therefore CED) is increased. This is an interesting result with regard to the European WEEE-directive, which is aimed at minimizing the amount of EEE waste that is sent to landfill.

If the aforementioned transparency of trade-offs could be provided before legislative procedures start, political decision-makers could gain a deeper insight into the impacts of legal measures. Non-intuitive results (e.g., increase in CED with a lower amount of land-filled waste) could be anticipated. Additionally, the level of effort necessary to fulfill new legal measures (e.g. high recycling costs necessary for minimizing the land-filled waste or high shadow-prices for CED) could be shifted to other processes or other product life-cycle phases, where higher environmental gains could be achieved with the same monetary efforts.

The proposed model provides decision makers with an easy tool for selecting the preferred solution regarding business and environmental indicators. For the German WEEE case, the decision maker can visually inspect the solutions and point his preferred one, and the model will indicate a network with decisions regarding end-of-life destination (i.e. recycling, landfill) and respective allocations. Furthermore, the model provides the trade-offs between waste ending in landfills and CED for supply chains with same costs. It is also possible to calculate the costs for reducing CED and landfilled waste, for different levels of the environmental indicators. Those results are not available for the aforementioned models based on single efficiency measures or methods based on linear programming weighting.

4.5 Conclusions and outlook

In this chapter we develop a methodology to explore Pareto optimal solutions for business and the environment. Our methodology allows decision makers to assess their preferred solution via one of the decision makers' most effective cognitive capabilities, visual inspection. Furthermore, the resulting iso-cost curves permit the assessment of the trade-offs among the environmental impact indicators and the profit of a given logistics network. In other words, the methodology helps to answer the questions: (i) How to determine the preferred solution(s) balancing environment and business? and (ii) what are the trade-offs between the aforementioned two dimensions? The emerging streams of research on eco-efficiency, namely, 1) methods based on single efficiency index, 2) methods based on weighting or 3) multi-objective methods based on the complete exploration of the extreme efficient vertices, do not provide satisfying solutions for the proposed questions. Furthermore, for the multi-objective methods, CPU-time grows fast with the size of the problem.

Identifying future research in this area is simultaneously an easy and a hard task. Easy because the methodologies available for MCDM and MOP have yet barely been applied for these specific problems. Methodologies such as ELECTRE for discrete problems, and Pareto-Race and STEM for continuous problems have not yet been explored for the assessment of preferred solutions for business and the environment. Hard because it is not clear which existing methods will bring better results. Further research on the most relevant phases for improving eco-efficiency (i.e. in a logistics network, transportation, manufacturing, procurement, end-of-use) has to be carried out, as well as on the computational difficulties of the models.

Chapter 5

Marketing used and remanufactured electrical and electronic products

5.1 Introduction

The marketing of second hand products is a multi-billion dollar business. In the United States alone, it is estimated that the market of used products has a turnover of approximately US38 billion (Lund [1998]). Consumers auction their used belongings on electronic platforms, such as eBay. Some companies re-sell their own products, sometimes after testing, repairing, re-furbishing or remanufacturing. Prior research has been carried out, under the brand name of closed-loop supply chains, concerning the planning, implementation, and controlling of the flow of these products from customers to manufactures, and back to customers (for reviews see Fleischmann et al. [1997] and Rubio et al. [2006]). Although the flow of these materials has been extensively studied, there has been much less research on their marketing[1](Guide and Van Wassenhove [2003]).

The question of what drives the prices of used, refurbished and remanufactured products, for instance, has been barely addressed. This question encompasses a number of other questions, such as: to what extent do consumers value more a

[1]A possible explanation is lies in the background of the researchers in the field, which is heavily skewed towards operations research and operations management

product that has been remanufactured by the OEM vis-a-vis a product that has been remanufactured by a third parties? How would different semantic cues (e.g. “as good as new”,“ almost new”) present in advertisements affect price perception? What is the effect of external reference prices (ERP) such as the listing price of a new product on consumer’s buying behavior of second hand items?

Our investigation focuses on the effect of the mentioning the price of a new product as an external reference price for a used similar product. Our research is motivated by the practice of using listed prices of new products as reference for used products with the same or similar functionalities. For example, Apple Computers uses the price of new iPods as reference prices for its refurbished (previous generation’s) iPods advertised in its online shop (http://store.apple.com/us). The electronics manufacturer also uses similar external reference prices on the advertisements of iMac computers. Third party remanufacturers, such as King remanufacturer (www.toolking.com) use the listing price of the original manufacturer as ERP.

The merchant-buyer reference prices effect in buying decisions are not unknown. In fact, the use of reference prices is regarded as a marketing tool that works remarkably well (Lichtenstein and William [1989], Urbany et al. [1998], Grewal et al. [1998]). Findings from diverse investigations suggest that reference price advertisement have a robust effect on buying decisions (Berkowitz and Walton [1980], Della Bitta and McGinnis [1981], Bearden et al. [1984], Liefeld and Heslop [1985], Blattberg et al. [1995], Urbany et al. [1998], Kopalle and Lindsey-Mullikin [2003], DelVecchio et al. [2007]). A myriad of different reference prices, framing and contexts in which this references are inserted have been analyzed. A generalization of these findings can be found Aradhna et al. [2002]. More recently, the flurry of electronic transactions has drawn the attention to other two references: minimum bid and reservation price at auctions (Kamins et al. [2004], Dholakia and Simonson [2005], Ku et al. [2006], Lucking-Reiley et al. [2007]).

Our investigation focuses on the effect of mentioning the price a new equipment on the WTP for its used counterpart. This particular ERP is the main focus of our research, and has not been addressed in previous studies. Furthermore, we are interested on the aforementioned effect in online shopping, rather than the traditional brick-and-mortar shopping. The reasons for that are (i) online shopping is flourishing, and there is a visible trend towards the increase in electronic shopping (Guardian [2008]), (ii) online stores are the favored outlet for a number of companies engaged in selling reused, refurbished and remanufactured products (i.e. Apple and IBM computers), and (iii) the experiments can be performed in a real setting, i.e. eBay, increasing the validity of the experiments.

5.2 The effect of external reference prices on consumers' buying behavior

The external reference price is a piece of information provided by the retailer that signals the discount in the offering (Biswas and Blair [1991]). This comparative price is referred to as an external reference price because it serves as an external reference for the price being offered (Lichtenstein and William [1989], Biswas and Blair [1991], Grewal et al. [1998], Urbany et al. [1998], Kopalle and Lindsey-Mullikin [2003]). ERPs appear in a myriad of different forms, such as "$X, now $Y", "compare at $X", "list price $X, our price $Y", "save $X%" (Biswas and Blair [1991]). This extra price information pervades advertising. In the United States, in 1998, more than 60% of the department store sales were sold at discount prices. This proportion increased to 75% in 2001 (McIlhenny [1989], Vreeland [1991] and Kaufmann et al. [2001]). The reason why products on discount are so ubiquitous is that reference prices simply work. Research suggests that it enhances the perception of saving (Blair and London Jr [2006], Grewal et al. [1998]), it raises the perceived value of the product, improves the attractiveness of the advertised deal, and increases the likelihood of purchase. Furthermore, it reduces the search for other offers, and increase willingness to buy (Della Bitta and McGinnis [1981], Lichtenstein and William [1989], Blattberg et al. [1995], Suter and Burton [1996], Urbany et al. [1998], Grewal et al. [1998]).

The aforementioned research has mainly focused on the brick-and-mortar environments. In online auctions two other reference prices have drawn substantial attention from academia and practitioners: minimum bids and reserve prices (Kamins et al. [2004], Dholakia and Simonson [2005], Ku et al. [2006], Lucking-Reiley et al. [2007]). Kamins et al. [2004] and Ku et al. [2006] suggest that lower starting prices attract more bidders and yield higher final prices via-a-vis higher starting prices. Conversely, the investigation of Lucking-Reiley et al. [2007] find a positive correlation between the minimum price and final value for auctions with less than one participant, and no significance for auctions with more than two participants. Kamins et al. [2004] finds that auctions with high price signals (reservation prices) yield higher final prices than auctions with low price signals (minimum bid), and that auctions with high signal price (reservation prices) and low price signals (minimum bid) result in higher prices vis-a-vis auctions with low price signals only (minimum bid).

5.3 The effect of reference prices: the "Anchoring" effect

The outcome of most decisions we make is dependent on variables that we cannot predict or control. In such cases, the decisions we take are predominantly based on the perceived likelihood of their outcome. Starting a new company, enrolling in a Bachelor in business, or making an offer for a new house are examples of everyday decisions we have to take that are surrounded by uncertainty. Economic growth and job market, are uncontrollable variables that can determine the outcome of such decisions. In these situations, we predominantly choose based on simple heuristics, which may lead sometimes to systematic distortions. Anchoring is an example of a phenomenon observed when we apply such heuristics (Tversky and Kahneman [1974]).

An anchor is a starting value or starting point, which is updated until the final decision or estimate is made. This estimate defines the expected outcome of a given decision, and drives the decision process. The aforementioned example of making an offer for a house, for instance, is significantly influenced by the present listing price (Northcraft and Neale [1987]). Fiedler [1999] defines an anchor as "a starting value, which may be chosen arbitrarily, [that] is repeatedly updated or adjusted in light of the relevant information until a final estimation is reached".

Anchoring is a very robust phenomenon in a number of situations. Anchoring effects have been observed on the context of judicial judgments (Englich and Mussweiler [2001]), clinical trials (Friedlander and Stockman [1983]), assessment of the likelihood of a nuclear holocaust (Plous [1989]), general knowledge quizzes (such as estimating the average temperature in Germany in Mussweiler and Englich [2005], the freezing temperature of vodka in Epley and Gilovich [2001], the altitude of Ulm, the year of birth of Da Vinci (Strack and Mussweiler [1997]), probability assessment(Wright [1989], Joyce and Biddle [1981], Tversky and Kahneman [1974]) or business transactions (Ariely and Simonson [2003], Chertkoff and Conley [1967], Galinsky and Mussweiler [2001a], Galinsky and Mussweiler [2001b], Joyce and Biddle [1981], Liebert et al. [1968], Northcraft and Neale [1987], Mussweiler et al. [2000]).

The anchoring effect is robust even with experts in high-stakes' decisions (Wansink et al. [1998]), such as real estate agents assigning value for real state properties (Northcraft and Neale [1987]) or consumers assigning value to cars (Mussweiler and Strack [1999]). Examples of counter-anchors are rare. One example of an anchor with an inverse effect is the minimum initial bidding price in auctions (Ku et al. [2006]). Ku et al. [2006] suggest that high minimum bidding prices may inhibit bidders to engage in the auction. Furthermore, they suggest that the number of bidders is positively correlated with the final price of the auction. (Ku et al. [2006]). The effect of minimum bidding price and minimum reserve price as anchors in auctions is the focus of many recent investigations (Greenleaf and Sinha [1996], Kamins et al. [2004], Ku et al. [2006], Simonsohn and Ariely [2005]).

Marketing research has also used the effect of anchoring to understand how consumers decide on the quantity they buy (Wansink et al. [1998]), on WTP (Nunes and Boatwright [2004], Krishna et al. [2006], Ariely and Simonson [2003]). Consumers anchor prices even when comparing products that are completely different. Krishna et al. [2006], for instance, observes that presenting a high-priced pen can impact the WTP for a camera. The effect is stronger for similar products that share some attributes. We hypothesize that the price of a remanufactured product is anchored by the price of a similar new product of its kind. We expect, therefore, that showing a used product in a new model that vaguely has the same functionality will anchor the price of the used equipment.

5.4 Motivation and research questions

As discussed in the initial chapters, a fraction of the returned electronic equipments is re-directed back to the consumer market. A number of marketing questions arises when the product is ready to be re-sold as a used or remanufactured equipment (e.g. how to advertise and price the product? Which market channel to use?). These decisions will particularly impact OEMs and independent remanufacturers, as the margins for electronics are particularly low and, therefore, every extra penny counts.

Concerning advertisement, ERPs are well reported as a way to increase revenues. For used and remanufactured electronics, it is expected, therefore, that presenting the price of a latest model of the product being sold will increase the WTP for the product, and therefore reservation prices and final prices in auctions.

Examples of advertisements in online shops indicate that OEMs and third party brokers and remanufacturers do not agree, or are not aware, of the importance of ERP. Take as an example two well-known OEMs engaged in remanufacturing: IBM and Apple computers. Apple anchors the price of every refurbished product sold on its online shop by the price of a new counterpart, no matter whether the anchor is an identical new product, or not. Regarding iPods, for instance, the price of the latest version appears as a comparison to the price of the remanufactured previous version being sold. On the other hand, IBM does not anchor the price of its remanufactured products on the price of new ones. Figure 5.2 shows ads of IBM and Apple computers. Another example of seller that presents the price of new counterparts on its merchandize's advertisement is Tool King remanufacturer (www.toolking.com). The company is a third-party remanufacturer, and deals with equipments from a myriad of different brands, including DeWALT, and Makita. For every product displayed in the online shop, the original price of the equipment is also presented. Sometimes companies use anchoring distinctively within the same line of products, such as the "renew series" from HP. For database storages, listed prices and the discount over the new product is presented. For desktop computers, no price reference is available. An example of third party remanufacturer that does not list the price of the new counterpart is Cellplex (www.cellplex.com). The XEROX outlet online (http://www.office.xerox.com/programs/factory_outlet.html) shop also does not provide any comparison between the sale price and the any other price that could serve as a ERP.

The types of ERP also vary between sellers. For Apple computers, the ERP is the price of the equipment listed in its own online shop. For Kingtoll remanufacturers, the reference prices are the listed prices of the remanufactured equipments. Other ERP used could be the price of the equipment when it was first launched or bought (for customers selling on auction platforms, such as eBay). It could also be the price of similar equipments, such as the price of the new versions of an iPod, as it is presented in the Apple online store.

The literature on the ERPs for mortar-and-brick retailers, does not address the effect of price of new products as reference price. The studies ERPs are the original price before discount and the price of competitors. In the online market, the ERPs analyzed are the minimum bid and the reservation price. We contribute to the understanding of the effect of the price of a new product as a reference for the reservation price and final price of a similar used product in an online setting. We

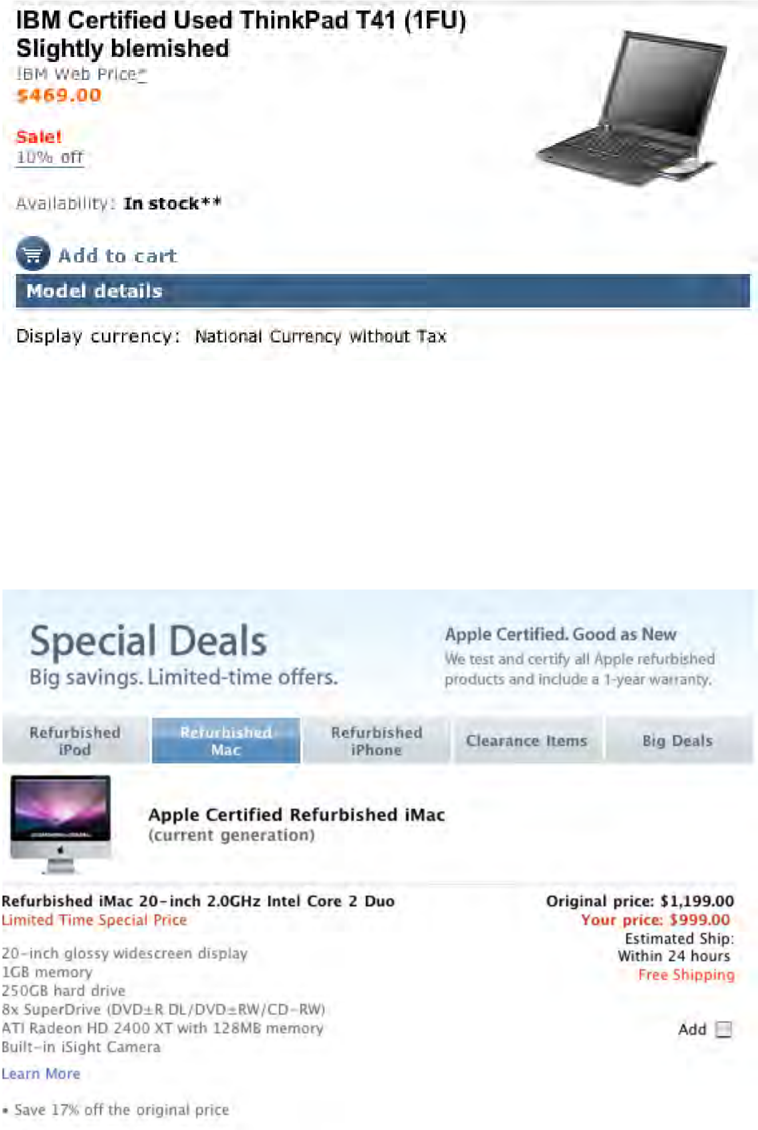

Figure 5.1: Advertising on the online shops of IBM and Apple computers

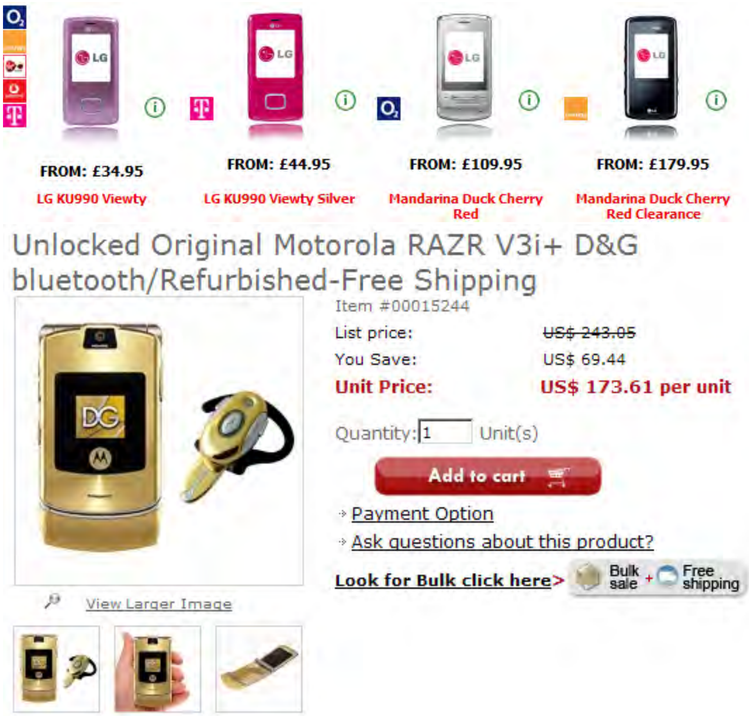

Figure 5.2: Mobile phones displayed on online shops of third-party remanufacturers with and without anchor

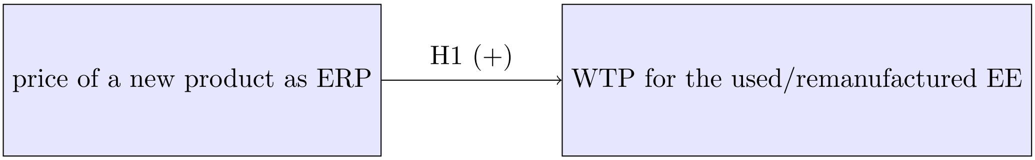

Figure 5.3: Effect of Anchoring of final prices of electronic equipments

study the impact of presenting the price of a similar product as an anchor for the price formation of a similar used product.

Hypothesis 1. *An advertisement of a second hand product with high price signal (price of a new counter part) and the description with aforementioned counterpart results in higher WTP vis-a-vis an advertisement with the comparison only and no high signal price.*

Hypothesis 2. *An advertisement of a second hand product with high price signal (price of a new counterpart) and a comparison with the aforementioned counterpart results in higher WTP vis-a-vis an advertisement with no comparison nor reference price.*

We acknowledge that our hypotheses and therefore results are specific for used products, and that under similar framing one could infer on much more generalizable settings. The effect could be caused by the reference of a similar product, regardless of the new/used relationship the two products share. The reason for focusing on used products is twofold: (i) the problem is relevant enough by itself. The market of second hand items is so big that the results are worth studying even if restricted to the aforementioned setting, and (ii) to the best of our knowledge, no research has been developed to determine casuality between a reference price of a similar product and the final price of the product itself in an online auction.

5.5 The experiment

In our study we document the effect of ERP on the WTP of used electronics. In this study we use two products that are familiar to our respondents: personal computers (PCs) and MP3-players. The objective of the study is to evaluate the effect of ERP (in our case, the price of a equipment similar to the one being sold) on the WTP of a used or remanufactured equipment.

5.5.1 Participants

Participants were 537 students enrolled at a large business school in The Netherlands. The students were divided in three groups. For each of the groups, students were asked how much they would pay, separately, for a given used computer and MP3-player.

5.5.2 Design

The participants were divided in three groups. The first group is exposed to an advertisement of a used personal computer. The information provided is the main information on the components of the computer (i.e. memory, speed, model). The group is also exposed to an advertisement of a used MP3-player. Again, information regarding functionality is provided. The second group receives the same information, and a comparison between the functionality of the equipment, and the functionality of the latest model available. The price of the latest equipment (computer) is also provided. We do the same for the MP3-players. The third group receives the same information as the second group, but not the price of the latest available equipment. For each of the groups, the main question regarding WTP was assessed directly: *"How much would you pay for this equipment?"*. One of the ads created for computers is shown in figure 5.5. This ad presents a comparison between the product being sold and a new counterpart. Furthermore, it presents the price of the new product. Another ad is presented without the ERP. A third one is presented without the ERP or the comparison. The other ads can be found in the annexes. On the same vein, figure 5.4 is the ad created for iPods. The other ads can also be found in the appendixes.

The participants answer the survey online at a time convenient for them. They are also encouraged to consider some time to search for similar products on the internet. The objective of this setting is to emulate an online shopping environment, were information can be cheaply and easily obtained via the web. Increasing the levels of information makes the survey a closer emulation of a real online buying situation.

Figure 5.4: Advertising for iPods used in the experiment. The ad presents no comparison with a new product and no ERP

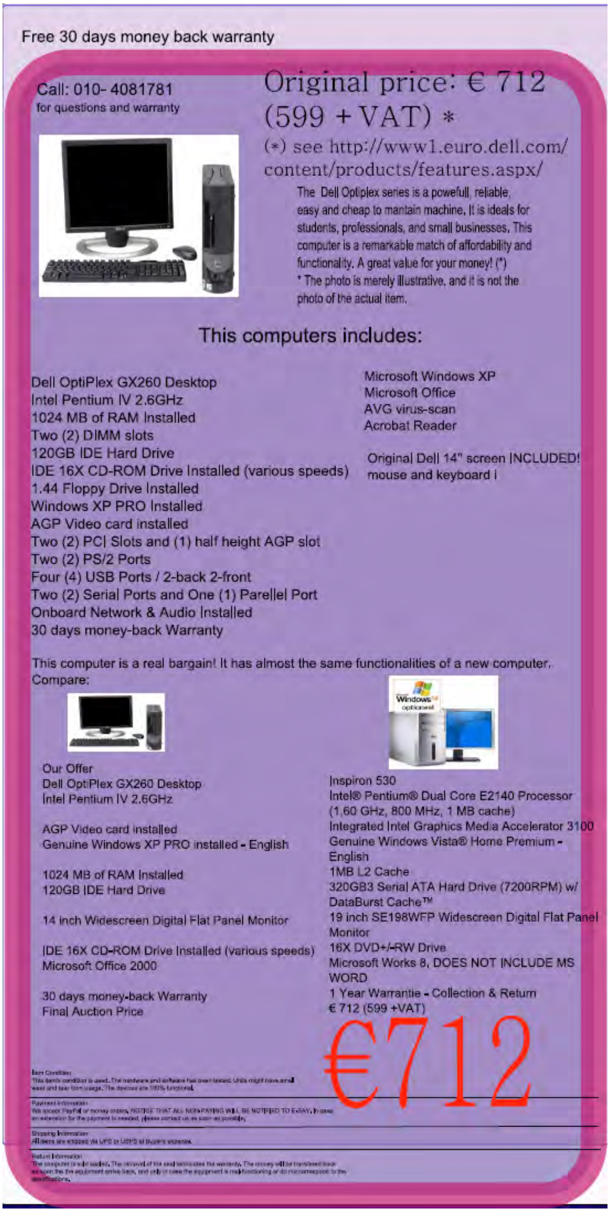

Figure 5.5: Advertising for computers used in the experiment. The ad presents a comparison with a new product and ERP.

5.5.3 Results

We are interested in the mean differences in WTP for the used equipment. We analyze the aforementioned three groups for each of the products (i.e. computers and MP3-players).

- ***lowinfo***. These ads only show the information regarding the functionality of the product. They provide no information regarding a new counterpart of the product being sold. These ads can be found in the appendixes.
- ***prodinfo***. These ads show the same basic information as in *lowinfo*, plus the comparison between the features of the product being sold and the features of the latest model of a equivalent equipment. These ads can be also found in the appendixes.
- ***ERPinfo***. For the last group show the same information as , plus the information on the price of the latest counterpart. The information of price of the latest counterpart is the ERP. These ads can be also found in the appendixes.

The number of respondents for the groups *lowinfo*, *prodinfo* and *ERPinfo* were , respectively, 135, 134 and 141. Among the respondents, only 14.7% acknowledge being familiar with purchasing second hand computers. As for MP3-players, the portion raises to 37.8%. In resonance with these results, the proportion of respondents declaring familiarity with the purchase of second hand electronics is 28.1% . Furthermore, only a fraction has ever bought a second hand computer or MP3-player (17.3% for computers and 10.8% for MP3-player). The sample shows unfamiliarity with the purchase of such equipments.

The average WTP for computers in the *lowinfo* group is €343.65. As for the *prodinfo* group, this average is slightly decreased increased to €345.48. Including the price of the latest model in the description (*ERPinfo*) increases prices to €400.30[2]. We use the Levene's homogeneity-of-variance to show that the variances are homogenous and pairwise one-way ANOVA to test for differences in mean.

The average WTP for MP3-players in the *lowinfo* group is €85.07. In the *prodinfo* group, this average is slightly increased by to €94.81. Referencing the price of the used equipment in the usage of a new product increases the WTP to €110.80 The

[2]Due the fact that some participants entered extreme values, we transformed the data using the Windsorizing procedure (Barnett and Lewis [1978]. Bottom and top 5% are replaced by the cut-off data. Furthermore, we eliminated all the data regarding values higher than the price of the product being advertised

difference in average among the three groups is significant at the 5% level, pairwise. We again use the Levene's homogeneity-of-variance test and ANOVA.

	Personal Computers			MP3-player		
group	mean	std. error	mean difference	mean	std. error	mean difference
lowinfo	€343.65	13.16	(0, -1.83, -56.66*)	€85.07	3.22	(0,-9.74*, -25.73**,)
prodinfo	€345.48	13.53	(1.83, 0, -54.82)	€94.81	3.87	(9.74*, 0, -15.99**)
ERPinfo	€400.30	12.80	(56.61*,54.82*,0)	€110.80	3.40	(25.73**, 15.99**)

Table 5.1: Differences in WTP for computers and iPods with different informations. * ($p \leq 5\%$), ** ($p \leq 1\%$)

5.5.4 Discussion

The difference in average WTP between the *lowinfo* and *ERPinfo* groups strongly supports hypothesis I. Pairwise ANOVAs for computers and MP3-players show that the difference in average WTP is statistically significant ($p \leq 0.01$). The result suggests that comparing a used product with a similar new counterpart does increase WTP. Furthermore, the average increases in WTP for computers and MP3-players are substantial and can significantly increase the profit of re-sellers of second hand products.

The difference in average WTP between the *prodinfo* and *ERPinfo* groups strongly supports hypothesis II. The difference between the two groups are statistically significant at ($p \leq 0.01$). The result indicates than advertisements including the price of a new product and the comparison between the two products work better that an advertisement with the comparison only.

Our results are aligned with the theory regarding ERPs and the effect of *anchors* in decision making (Urbany et al. [1998] and Tversky and Kahneman [1974]). External reference prices have positive effects in the WTP, WTB, perceived value of the others, as previously discussed. The literature as well as our results suggest that including the price of a new product on the advertisement of a used similar product will increase the WTP for the product.

It is also interesting to note that for MP3-players there is a significant difference in prices between the groups *lowinfo* and *prod info*. The effect does not concern the hypotheses being tested, but may point to interesting new research

5.6 Limitations and further research

One of the limitations of our approach has been documented in the fields of psychology and marketing. WTP is a measure difficult to assess. Although it is widely used, reported WTP does not necessarily match with the real WTP of respondents.

The solution for such limitation is to analyze real transactions via B2C platforms such as eBay. The analysis is usually carried out in two ways. In the first appraoch, one observes an item that is commonly auctioned and keeps track of the results. Another common approach to isolate the influence of a certain phenomena in pricing is carrying out auctions, changing the information provided. In other words, the second approach would be, for our investigation, to perform the same experiment we presented in this chapter, in a real auction setting. This approach has been used by Kamins et al. [2004], Dholakia and Simonson [2005], Ku et al. [2006], Lucking-Reiley et al. [2007] for the study of ERPs on auctions.

A number of other questions have not been addressed in this chapter and are potential areas of interest for further research. Which anchor works better for remanufactured equipments? Would it be the price of a similar counterpart? What should be the counterpart used: the equipment with current listed prices that reassemble the one on sale or the one with the highest price (similarity versus price)? The listed price of the equipment at the time it was launched? The list price of the equipment when it was discontinued? Are the results product dependent? We point to these questions as future research.

Chapter 6

Conclusions

6.1 Summary of the main results

This chapter describes the main findings and contributions of this thesis. Our investigation focuses on a variety of issues regarding sustainable supply chains and eco-efficient supply chains, in particular within the context of electrical and electronic products. The next sections summarize the main results. We use the same structure used in chapter 1 and separate the thesis in three parts.

Part I

The first chapter of this thesis is an introduction to the field of sustainable supply chains. We reviewed in this chapter the main challenges ahead of a sustainable society. We also presented empirical evidence on the pursuit of sustainability by consumers, NGOs, companies and governments. We also presented such evidence for the particular case of electrical and electronic equipment. Furthermore, in Chapter 1 we defined what we understand to be an sustainable and an eco-efficient supply chain.

Chapter 2 was devoted to the study of the environmental footprint of electrical and electronic products. In this chapter, we analyzed the impact that the many phases of the life cycle of electrical and electronic products have on the environment. More specifically, we analyzed the effect that some product recovery initiatives (i.e. reuse, refurbishing and remanufacturing) have on the environment. These objectives are translated into the following research questions:

RQ1: What are the phases of the life cycle of electrical and electronic products that impact the environment the most?

RQ2: Which activities within the reverse logistics of electronics (i.e. recycling, remanufacturing) can effectively mitigate the environmental footprint of the electrical and electronic supply chain?

For the electrical equipment we analyzed, the usage phase consumes most of the energy demanded during the entire life-cycle. In most cases, the usage phase consumes more than 90% of the total energy. The energy profile consumption is very robust regarding all LCAs included in the investigation. Manufacturing and transportation play a small role in the amount of energy used.

Also, for the electrical equipments analyzed, extending their life-span reduces final waste streams. On the other hand, however, reuse, refurbishing and remanufacturing do not significantly decrease the CED.

For the electronic equipments analyzed, due to their short life cycles and to the presence of energy intensive parts, the manufacturing phase demands most of the energy used during their life cycles. The results are robust for both computers and mobiles, regarding almost all LCAs used in this investigation. Usage and transportation play a minor role in the amount of energy used.

Furthermore, for the above electronic equipments, both final waste stream mitigation and reduction in CED can be achieved by increasing their life span. Reuse, refurbishing and remanufacturing are, therefore, effective ways to decrease the environmental footprint of these products. This result is in resonance with the claims found in the CLSC literature. This result is useful for OEMs as it points to the direction in which companies should concentrate their efforts. These findings are also important for legislators. They can be used to support the design of new environmental legislation (such as the European IPP), as they show that reuse, refurbishing and remanufacturing should be a priority, as opposed to recycling.

Part II

In the second part of the thesis we focused on the design of the recovery networks of electrical and electronic equipments. More specifically, we studied the design of eco-efficient recycling networks. Our research question was the following:

RQ3: Which multi criteria decision making (MCDM) methods can be used to support decision aid in sustainable supply chains?

We proposed a methodology to design the recovery supply chain of electronic equipments, with environmental and economic objectives to be optimized. Despite the extensive literature regarding the design of recovery networks, our approach is to the best or our knowledge the first formulation incorporating both the environmental dimension and costs simultaneously.

Furthermore, we discuss which methods can be used to elicit preferences regarding the proposed formulation. We review the main methods to solve MOP and we posit the exploration of the efficient frontier is the one that better suits our needs: (i) evaluation of the current efficiency of the networks, and (ii) eliciting the trade-offs between the three aforementioned objectives (costs, waste and CED). We also conjecture the that, within the methods to explore the efficient frontier, the complete exploration of the efficient vertices is not a suitable approach due to very large CPU-times.

Furthermore, we present a framework to translate our results into a DEA environment, making it possible to evaluate the efficiency of existing recovery network with the methods available in DEA.

In Chapter 4, we develop a simple methodology to explore the eco-efficient frontier proposed in the previous chapter. The formulation runs in polynomial time, and therefore overcomes the possible computational intractability of finding all extreme efficient points. We illustrate our finding with the design of a recovery supply chain of electronics located in Lower Saxony, Germany.

Using the proposed methodology, we show, for this example, that there are almost inevitable trade-offs between the increases in recovery volumes and CED, regardless of the incurred costs. The reason for such apparent paradox[1] is that transportation drastically increases with volume recycled.

[1] As mentioned in Chapter 3, recycled materials usually consume a fraction of the energy necessary to produce new products. Recycled aluminium, for instance, consumes approximately 4% of the energy used in the production of new aluminium (The Economist [2007b])

Part III

The last chapter of the thesis deals with the marketing issues of remanufactured and used electronics. We are interested in ways to increase the final prices of reused, refurbished and remanufactured products. The research question is:

> RQ4: Which information could potentially increase the WTP for used remanufactured and refurbished equipment?

We present what we believe are the relevant questions for research in the field and we explore one of them: when and how could the anchor effect be used to increase WTP for used and remanufactured products? In more detail, we analyze whether displaying the price of the latest models of equipment that resemble the one being sold would increase the WTP for the product. We also propose the study of different types of anchors, and the effect of them on the final WTP for used and remanufactured equipments.

We find that using the price of equipment that resembles the one being announced as a external reference price (ERP) increases the price of the latter. We also documented that the effect of ERP is observed regardless whether of comparison between the two products is provided.

6.2 Future research

As the field of sustainable supply chains is still in its infancy, the number of unanswered interesting research questions outnumbers the number of questions answered. We point out here the ones that we find more relevant and, admittedly, the ones that we find sheerly more interesting. We believe that there are many other interesting questions waiting to be discovered and answered, but for those we have no map, no track to find them.

As for the design of sustainable supply chains, many interesting questions have arised during our research. One fundamental questions that has not been approached in this thesis is whether an OEM could reclaim extra cheap carbon via remanufacturing. In other words, if an OEM decides to remanufacture electronics that are not economically viable, but environmentally beneficial, would we be able to regain carbon (considering that a certain percentage of the new product will not be manufactured) for prices below carbon market prices, for instance? In other words, can the environmental gains be so appealing that we might change the threshold price which defines whether a product is remanufactured or merely discarded? In that case, what would be the new threshold? What is the economic interpretation of this new threshold? In other words, what is the cost of carbon considering the new price cut? We have shown that remanufacturing is *effective* on reclaiming energy and mitigating waste, but the question: *"Is remanufacturing an efficient way of reclaiming carbon?"*remains unanswered .

The second part of this thesis discusses the design of eco-efficient supply chains. We devote our efforts to the design of recycling networks for electrical and electronic products.

A number of other classic problems in CLSC, however, can also be extended to include environmental dimensions. Take, for instance, the economic lot size problem with remanufacturing, as presented in Golany et al. [2001] and Tang and Teunter [2006]. In such problems, the OEM has to decide which products to remanufacture and at which pace. A natural extension of the problem is to consider energy and waste as objectives to be minimized. Increasing the levels of remanufacturing for electronics decreases the CED and waste of such equipments[2]. The costs for such increase could be assessed via the enumeration of the efficient solutions of the problem. The efficient frontier would help us to answer the aforementioned question *"Is remanufacturing an efficient way of reclaiming carbon?"* for such manufacturing and remanufacturing settings, for instance.

Naturally, other questions have also arisen regarding the marketing of used and remanufactured equipment. Due to the novelty of the intersection between marketing and closed-loop or sustainable supply chains, a number of questions are still to be answered.

In Chapter 6 we raise the question on whether we could manipulate the use the Anchor effect to increase final prices of remanufactured products. We have not addressed, however, which type of anchoring would render better results: anchoring the product on the price of a new counterpart, anchoring the price on the price of the most expensive available new counterpart, anchoring on the price of the product that resembles the most the one on sale, on listing price of the displayed product in the date it was launched, etc.

In the literature review for Chapter 6 we briefly described two topics that we that have also found quite appealing to study, and that have not been addressed in

[2]such as computers and mobiles, as described in Chapter 2

this thesis. First, we mention the effect of information asymmetry on the market of remanufactured products. In the market for second hand products, such as the market for second hand cars, one of the parts of the transaction (seller) has more information than the other (buyer). Market with such asymmetries in information are less efficient than markets in which the same information is available for both parts (Akerlof [1970]).

Another interesting avenue of research concerns the mitigation of such asymmetry. A fundamental question is how can the effects of such asymmetry be mitigated, and how would such mitigation impact the final price of the remanufactured products? A number of factors may help to mitigate this asymmetry. Warranties, the fact that the product has been remanufactured by the OEM as opposed to remanufactured by some third party remanufacturer, good reputation of the remanufacturer, the implementation of quality grades (such as the quality grades for used products in eBay) are some examples.

The second one regards the impact of information related to the environmental friendliness of used and remanufactured electronic equipments. Would providing such information increase WTP for these products? What is the proper way to convey such information in a trustful way, so that consumers do not perceive it as a sales gimmick? As environmental awareness grows, providing consumers with the environmentally friendly credential of some remanufactured products can help to increase the attractiveness of these products.

These research questions are left to be studied in coming research, and we believe they point to new interesting directions to the field of sustainable supply chains and eco-efficient supply chains for electrical and electronic products.

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Appendix A

Abbreviations

clsc: Closed-loop Supply Chain.

DEA: Data Envelopment Analysis.

DM: Decision Maker.

EEA: European Environmental Agency.

ERP: External Reference Price.

LCA: Life Cycle Assessment.

MCDM: Multi Criteria Decision Making.

MOLP: Multiobjective Linear Programming.

MOP: Multiobjective Programming.

OEM: Original Equipment Manufacturer.

OM: Operations Management.

OR: Operations Research.

ERP: External Reference Price.

WTP: Willingness to Pay.

Appendix B

Advertisements

Figure B.1: Advertising for iPods used in the experiment. The add presents a comparison with a new product and ERP

Figure B.2: Advertising for iPods used in the experiment. The add presents a comparison with a new product, but no ERP

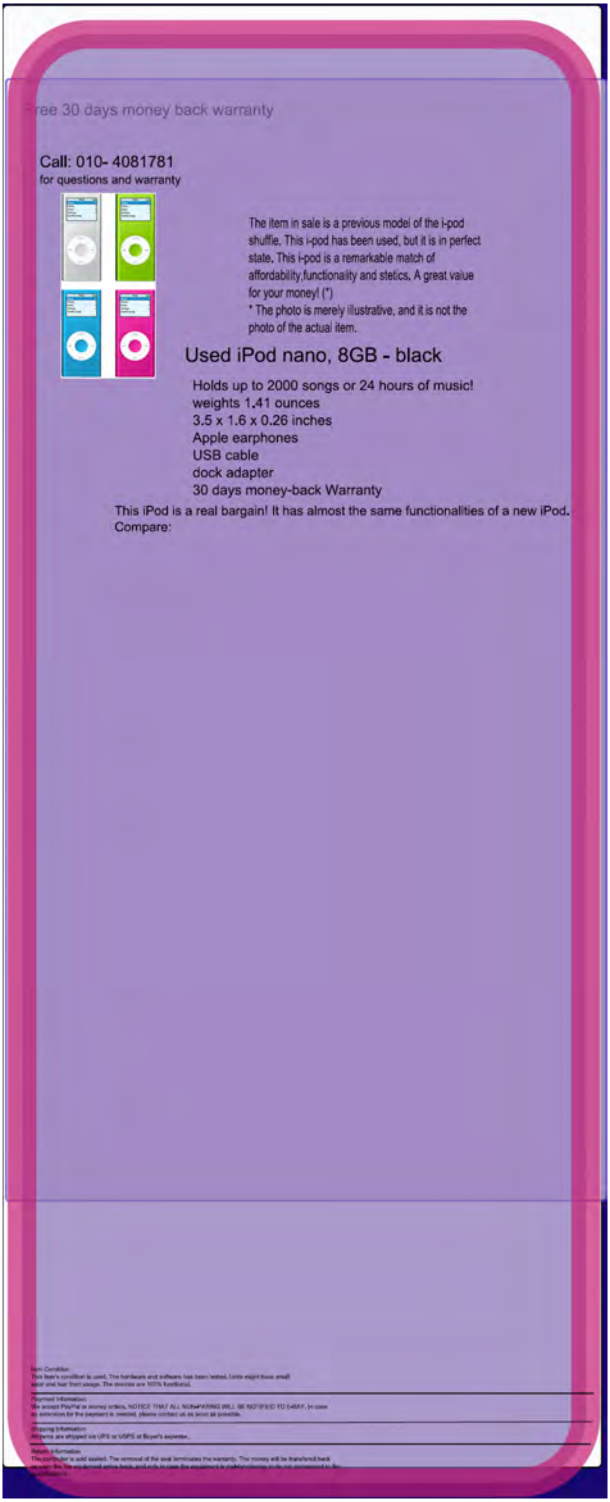

Figure B.3: Advertising for iPods used in the experiment. The add presents no comparison with a new product nor ERP

Figure B.4: Advertising for computers used in the experiment. The add presents a comparison with a new product and ERP.

Figure B.5: Advertising for computers used in the experiment. The add presents a comparison with a new product, but no ERP.

Figure B.6: Advertising for computers used in the experiment. The add presents no comparison with a new product nor ERP.

Appendix C

Environmental Data and Calculations

The following are calculations for Cumulative Energy Demand (CED) and waste presented in Chapter 2.

Table C.1: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer. The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

...lata	FFD†	CED‡	CED (%)	carbon off-set costs◇	monitor	main assumptions	calculations
...uring							
... and ...50	240^{l}	$5,040^{l}$	$74^{c(l,e)}\%$	$4.67^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature).
...2005] ...VAL-	N.A.	N.A.	$60^{c(l,e)}\%$	N.A.	CRT	N.A.	N.A.
... al. ... and ...50	N.A.	N.A.	$85^{l}\%$	N.A.			
...Con- ... and	172^{l}	$3,630^{l}$	$26\%^{l}$	$3.36^{c(l)}$	CRT	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 3,630/21 = 172$
	290^{l}	$7,320^{l}$	$83\%^{l}$	$6.77^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
	290^{l}	$6,400^{l}$	$81\%^{l}$	$5.99^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
... and ...50	80^{l}	$1,680^{l}$	$25\%^{l}$	$1.02^{c(l)}$	CRT	none	In Williams [2005] it is claimed that the energy consumed in the usage phase is $\frac{1}{3}$ of the energy used in the production phase. The energy consumed in the usage phase is, therefore: $\frac{1}{3} \cdot 5,040$. Considering the same FFD/CED ratio we calculate the CED and CED(%)
...2005] ...VAL-	$83^{c(l)}$	$1,740^{l}$	$39^{c(l,e)}\%$	$1.61^{c(l)}$	N.A.	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. We also assume that the computer has been used for two years	$FFD = 1740/21 = 129$
...a]	$93^{c(l)}$	$1,960^{l}$	N.A.	$1.81^{c(l)}$	LCD	We consider the following specifications: Intel Core 2 Duo,17 " screen, flat panel, in usage for 7 hour a day, maximum performance 1h a day.We assume that the computer has been used for 2 years.	$FFD = 1960/21 = 93$
... al. ... and ...50	N.A.	N.A.	$15^{l}\%$	N.A.	excluded	we approximate CED from GWP	N.A.
...7c]	$89^{c(l)}$	$1,872^{l}$	N.A.	1.80^{l}	LCD	We assume a 20-inch iMac, working 8h usage per day, 7 days a week, with Energy saver enabled. We also assume the same FFD/CED found in Williams [2005] to calculate FFD.	FFD=1872/21=89
...b]	N.A.	N.A.	N.A.	6^{l}	LCA	none	no calculations (values extracted directly from the literature).
...Con- ... and	$485^{c(l)}$	$10,200^{l}$	$74\%^{l}$	$9.43^{c(l)}$			
... LLC	78^{l}	$1,656^{l}$	N.A.	$1.53^{c(l)}$	laptop	based on the estimation for a laptop in 2005	no calculations (values extracted directly from the literature)
...t al.	N.A.	$1,500^{l}$	$17\%^{l}$	$1.39^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
	59^{l}	$1,270^{l}$	$19\%^{l}$	$1.17^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)

Table C.2: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer (cont.). The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

ation							
and 50	$1.4^{c(e,l)}$	28^{e}	1%	≤ 0.10	(-)	We assume that a computer travels $1,000km$ in a 16t truck and weights $10kg$	According to BUWAL-250, a 16t truck has the has the efficiency of 2.88MJ/t*km. The energy spent is, therefore $\frac{1,000 \cdot 10 \cdot 2.88}{1000} = 2.88$. Considering the ratio 21MJ/kg of fossil fuel (Williams [2005]) we have $\frac{28}{21} = 1.4kg$ of fossil fuel.
005] VAL-	$1.4^{c(e,l)}$	28^{e}	1%	≤ 0.10	(-)	We assume that a computer travels $1,000km$ in a 16t truck and weights $10kg$	According to BUWAL-250, a 16t truck has the has the efficiency of $2.88MJ/t*km$. The energy spent is, therefore $\frac{1,000 \cdot 10 \cdot 2.88}{1000} = 2.88$. Considering the ratio 21MJ/kg of fossil fuel (Williams [2005]) we have $\frac{28}{21} = 1.4kg$ of fossil fuel.

Table C.3: Cumulative Energy Demand for the different phases of the life cycle of a mobile phone. The analysis include the computer's monitor.FFD† is the fossil fuel demand in kg of fossil fuel.CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in U$ dollars. Source:www.carbonfound.org (CarbonFund [2007]).^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^\diamond$	main assumptions	calculations
Manufacturing						
Gotthardt et al. [2005] and BUWAL-250	$N.A.$	N.A.	$59^{c(l)}\%$	0.81	direct from literature.	
Singhal [2005]	$2.4^{c(l)}$	150^l	$60^l\%$	0.12	data comes directly from literature, for "light" usage. The data differs little from the "high" usage data.	$FFD = 60\% \cdot 4 = 2.4$
Frey et al. [2006]	$8^{c(l)}$	$(132 - 165)^l$	$50^{c(l)}\%$	0.15	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD	$FFD = 165/21 = 8$
McLaren and Piukkula [2004]	$7.6^{c(l)}$	160^l	$57^{c(l)}\%$	0.15	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 160/21 = 7.6$
Usage						
Gotthardt et al. [2005] and BUWAL-250	N.A.	N.A.	$41^{c(l)}\%$	0.55	direct from literature	
Singhal [2005]	$1.2^{c(l)}$	77^l	$29^l\%$	< 0.10	data comes directly from literature, for "light" usage. For "high" usage, the energy consumed in the usage phase is equal to 101MJ. It is assumed in Singhal [2005] that the mobile is used for two years	$FFD = 60\% \cdot 4 = 2.4$
Frey et al. [2006]	$6^{c(l)}$	116^l	$41^{c(l)}\%$	0.15	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. No information is available concerning the number of years the mobile is used	$FFD = 116/21 = 6$
Schaefer et al. [2003]	N.A.	$94^{c(l)}$	N.A.	< 0.10	data for annual consumption comes directly from Schaefer et al. [2003]. The energy consumption includes the energy dissipated by the mobile charger when charging a full mobile battery. We assume that the mobile is used for 2 years	(N.A.)
McLaren and Piukkula [2004]	$4.28^{c(l)}$	90^l	$32^{c(l)}\%$	< 10	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. It is assumed in McLaren and Piukkula [2004] that the mobile is used for two years	$FFD = 90/21 = 4.28$
Transportation						
Williams [2005] and BUWAL-250	insignificant	insignificant	$\leq 1\%$	< 0.10	We assume that a mobile travels $1,000km$ in a 16t truck and weights $0.13kg$ (Nokia [2007])	According to BUWAL-250, a 16t truck has the has the efficiency of 2.88MJ/t*km. The energy spent is, therefore $2.88 \cdot 1000 \cdot \frac{0.13}{1000} = 0.4$
Singhal [2005]	$0.5^{c(l)}$	28^l	$11^l\%$	< 0.10	data comes directly from literature	
Frey et al. [2006]	$1^{c(l)}$	31^l	$9^l\%$	< 0.10	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 31/21 = 1$
McLaren and Piukkula [2004]	$1.43^{c(l)}$	30^l	11%	< 10	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 30/21 = 1.43$

Table C.4: Cumulative Energy Demand for the different phases of the life cycle of a refrigerator. The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. ◇ prices are expressed in U$ dollars. Source:www.carbonfound.org (CarbonFund [2007]). ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED(%)	carbon offset costs◇		
Manufacturing						
Williams [2005] and BUWAL-250	53^{l}	$1,110^{l}$	$4^{l}\%$	1.04	data directly extracted from Williams [2005]. it is assumed a ten years life time for the refrigerator.	FFD=1110/21 = 53.
Steiner et al. [2005]	N.A.	N.A.	$20^{l}\%$	N.A.	data directly extracted from Steiner et al. [2005]. Production & distribution are aggregated in the work of Steiner et al. [2005]. Data include the percentages concerning CED only.	
Kim et al. [2006] and BUWAL-250	$286^{c(l)}$	$6,000^{l}$	$5^{c(l)}\%$	5.5	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD	data directly extracted from Steiner et al. [2005].
Otto et al. [2006] and BUWAL-250	$243^{c(l)}$	$5,100^{l}$	$7^{c(l)}\%$	4.72	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 1417/21 = 243$
Horie [2004] and BUWAL-250	$283^{c(l)}$	$5,940^{l}$	$6^{c(l)}\%$	5.49	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD.	$FFD = 5940/21 = 283$
Usage						
Williams [2005] and BUWAL-250	$1,277^{c(l)}$	$26,813^{l}$	$96^{l}\%$	24.8	data directly extracted from Williams [2005]. It is assumed a ten year life time for the refrigerator. It is also assumed that the energy consumption is $400kWg/year$.	FFD=26813/21 = 1277.
Steiner et al. [2005]	N.A.	N.A.	$80^{l}\%$	N.A.	data directly extracted from Steiner et al. [2005]. Data include the percentages concerning CED only	
Kim et al. [2006] and BUWAL-250	$5,400^{c(l)}$	113, 400	$95^{c(l)}\%$	105.5	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD	data directly extracted from Steiner et al. [2005].
Otto et al. [2006] and BUWAL-250	$3,071^{c(l)}$	$64,500^{l}$	$93^{c(l)}\%$	59.66	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. Otto et al. [2006] assumes a 15 year life time for a refrigerator.	$FFD = 64500/21 = 3071$
Horie [2004] and BUWAL-250	$4,326^{c(l)}$	$90,860^{l}$	$94^{c(l)}\%$	84.04	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. I assume a 10 year life time for a refrigerator.	$FFD = 90860/21 = 4326$
Transportation						
Williams [2005] and BUWAL-250	$9.6^{c(l)}$	$201^{c(l)}$	$1^{c(l)}\%$	insignificant	We assume that a refrigerator travels $1,000km$ in a 16t truck and weights $70kg$	According to BUWAL-250, a 16t truck has the efficiency of 2.88MJ/t*km. The energy spent is, therefore $2.88 \cdot 1000 \cdot \frac{70}{1000} = 201MJ$

Table C.5: Cumulative Energy Demand for the different phases of the life cycle of a tv set. The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. $\diamond$ prices are expressed in U$ dollars. Source:www.carbonfound.org (CarbonFund [2007]). ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon off-set costs$^{\diamond}$		
Manufacturing						
Steiner et al. [2005]	N.A.	N.A.	80^{l}%	(-)	data directly extracted from Steiner et al. [2005]. The television is a CRT type.	
Alting et al. [1997]	$222^{c(l)}$	$4,667^{l}$	22.6%	4.31	data directly extracted from Alting et al. [1997]	FFD=4467/21=222. The television is a CRT type.
Feng and Qian Ma [2008]	$454.4^{c(l)}$	$9,542^{l}$	22.88%	8.83	data directly extracted from Feng and Qian Ma [2008]. The television is a CRT type	FFD=9542/21=454
Takayoshi et al. [1999]	N.A.	N.A.	80^{l}%	N.A.	data directly extracted from Takayoshi et al. [1999]. The television is a CRT type.	FFD=4467/21=222.
Sony [2008]	N.A.	N.A.	13^{l}%	N.A.	It is assumed that the tv is used for 10 years. The model is a KDL-32S1000 LCD tv.	
Usage						
Steiner et al. [2005]	N.A.	N.A.	20^{l}%	(-)	data directly extracted from Steiner et al. [2005]. The television is a CRT type.	
Alting et al. [1997]	$762^{c(l)}$	$16,000^{l}$	77.4%	14.8	data directly extracted from Alting et al. [1997]	FFD=16000/21=762.The television is a CRT type.
ACE [2008]	$317^{c(l)}$	6,660	N.A.	6.16	we assume that the tv is in use for 10 years (185kWh/year)	FFD=6660/21=317. The television is a CRT type.
Sony [2008]	N.A.	N.A.	87^{l}%	N.A.	It is assumed that the tv is used for 10 years. The model is a KDL-32S1000 LCD tv.	
Feng and Qian Ma [2008]	$1,148^{c(l)}$	$24,115^{l}$	57.5%	22.30	data directly extracted from Feng and Qian Ma [2008]. It is assumed a 10 year live span.	FFD= 24115/21=1148
Transportation						
Alting et al. [1997]	insignificant	$< 400^{l}$	insignificant	<0.10	data directly extracted from Alting et al. [1997].	
Sony [2008]	N.A.	N.A.	insignificant	N.A.	It is assumed that the tv is transported 500 kilometers by truck in Japan.	
Feng and Qian Ma [2008]	$395^{c(l)}$	$8,280^{l}$	$19.7^{c(l)}$%	7.66	data directly extracted from Feng and Qian Ma [2008]	

Table C.6: Cumulative Energy Demand for the different phases of the life cycle of a washing machine. The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. ◇ prices are expressed in U$ dollars. Source:www.carbonfound.org (CarbonFund [2007]). ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon off-set costs◇	main assumptions	calculations
Manufacturing						
Steiner et al. [2005]	N.A.	N.A.	14^{l}%	N.A.	data directly extracted from Steiner et al. [2005]. Data for manufacturing & distribution are grouped together.	
LCAcenter [2005]	N.A.	N.A.	24^{l}%	N.A.	data directly extracted from LCAcenter [2005]	
Otto et al. [2006]	$1965^{c(l)}$	6100^{l}	$8^{c(l,e)}$%	$5.64^{c(l)}$	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD	FFD=6100/21 = 290
Throne-Holst et al. [2007]	$N.A.$	$N.A.$	$\leq 10^{l}$%	N.A.		
Usage						
Steiner et al. [2005]	N.A.	N.A.	86^{l}%	N.A.	data directly extracted from Steiner et al. [2005]	
LCAcenter [2005]	N.A.	N.A.	76^{l}%		data directly extracted from LCAcenter [2005]	
Otto et al. [2006]	$3,371^{c(l)}$	$70,800^{l}$	$92^{c(l,e)}$%	$65.5^{c(l)}$%	we assume the same ratio FFD/CED found in Williams [2005] to calculate FFD. Otto et al. [2006] assumes a 15 year life time for a washing machine	FFD=70800/21 = 3371
Throne-Holst et al. [2007]	$N.A.$	$N.A.$	$\geq 90^{l}$%	N.A.		
Transportation						

Sumário

Centenas de milhões de produtos elétricos e eletrônicos são remanufaturados a cada ano. Ademais, acredita-se que esse número não diminuirá nos próximos anos.

Consumidores, ONGs e governos são cientes do potencial risco que esses produtos representam, e por isso têm sistematicamente pressionado os fabricantes a reduzir o impacto ambiental causado por seus produtos e serviços. Os fabricantes, por sua vez, têm respondido à essa pressão e aumentado o número de iniciativas em favor do meio ambiente.

Essa tese é motivada pelo desafio de diminuir os impactos ambientais causados pelos inúmeros produtos elétricos e eletrônicos que fazem as nossas vidas mais confortáveis e agradáveis. Espeficicamente, a tese trata do desafio de reduzir esses impactos de forma eficaz e eficiente. Uma das conclusões da pesquisa é que as empresas do setor precisarão de um conjunto de diferentes estratégias para alcançar esse objetivo. Ademais, essas estratégias deverão levar em conta fatores ambientais, técnicos e de mercado. Estes três aspectos devem ser considerados de forma sistêmica, e as soluções irão variar de acordo com as empresas, os produtos que elas fabricam as maneiras em que as cadeias de produção são organizadas.

As principais descobertas dessa tese são as seguintes.

- Diferentes tipos dos produtos elétricos e eletrônicos apresentam um perfil de consumo energético referente às diversas fase de sua vida (i.e. manufatura, transporte e uso) radicalmente diferente entre si. A proporção de energia usada na fabricação de uma geladeira, em relação às demais fases do seu ciclo de vida, é radicalmente diferente da mesma proporção para computadores, por exemplo. A legislação referente a esses produtos deve considerar essas diferenças fundamentais. Para alguns produtos, remanufatura deve ser encorajada. Para outros, reciclagem.

- No que se refere aos dois produtos eletrônicos mais manufaturados, computadores pessoais e telefones celulares, remanufatura é uma solução extremamente eficaz na redução do impacto no meio ambiente. Uma das decisões mais importantes é, portanto, a decisão de remanufaturar ou não esses equipamentos. A razão para tal é que a maior quantidade da energia utilizada durante a vida desses equipamentos é consumida durante a fabricação dos mesmos. Ademais, não é possível recuperar essa energia por meio de reciclagem. Um outro aspecto benéfico da remanufatura é que esta pode, potencialmente, diminuir o fluxo de equipamentos que é descartado através do retardo da fabricação de novos produtos.

- No caso de produtos que não se adequam mais à remanufatura, e são portanto destinados à reciclagem, os fatores mais significativos no que se refere à conservação de energia e diminuição do fluxo de descartes são as localizações das instalações de reciclagem e descarte, e os níveis de reciclagem adotados.

- Tratando-se dos modelos matemáticos utilizados no planejamento de redes de reciclagem nos quais volume de lixo, energia e custos são considerados, a numeração exaustiva das soluções pareto-eficientes é impossível, dada à cardinalidade do conjunto dessas soluções. Nós propomos uma simples heurística para ajudar na escolha de soluções considerando estas três dimensões e para auxiliar na visualização dos referentes *trade-offs*.

- Consumidores, em geral, exigem um considerável desconto na compra de produtos remanufacturados. Ademais, pouco se sabe a respeito dos fatores que criam tal desconto. *External Reference Prices (ERPs)* são um desses fatores e influenciam significativamente esses preços. Entender os fatores que geram esses descontos, e agir para mitigá-los é uma maneira eficiente de aumentar e eco-eficiência no setor de elétricos e electrônicos.

Samenvatting

Elk jaar worden honderden miljoenen elektrische en elektronische apparaten gefabriceerd. Dit aantal zal zeker niet substantieel afnemen in de nabije toekomst. Consumenten, NGOs en overheden hebben erkend dat deze producten een bedreiging kunnen vormen voor het milieu. Zij hebben bedrijven dan ook aangespoord om de impact van hun producten en diensten op het milieu te reduceren. Als antwoord op deze overheidsdruk hebben bedrijven een aantal milieuvriendelijke initiatieven genomen.

Deze thesis bespreekt hoe we de impact van elektronische en elektrische producten op het milieu op een efficiënte en effectieve manier kunnen verminderen. We tonen aan dat bedrijven een mix van strategieën nodig hebben om deze uitdaging aan te kunnen. Deze strategieën moeten tezelfdertijd milieu-gerelateerde aspecten, technische aspecten en marketing aspecten in overweging nemen. We vinden ook dat de aangeboden oplossingen drastisch variëren naargelang de aard van het bedrijf, het product dat het bedrijf fabriceert, en de manier waarop de supply chain georganiseerd is.

De voornaamste bevindingen van deze thesis zijn meer specifiek:

- Verschillende elektrische en elektronische toestellen hebben een radicaal verschillend energieconsumptiepatroon doorheen hun levenscyclus. De hoeveelheid energie die nodig is om een computer te produceren (in verhouding tot de totale energie verbruikt over de levenscyclus van dit toestel) is bijvoorbeeld drastisch verschillend van de energie nodig bij de productie van een koelkast. Wetgevers moeten deze fundamentele verschillen in acht nemen bij het uittekenen van hun milieubeleid. Meer in het bijzonder dient de milieuwetgeving inzake elektronische en elektrische toestellen productspecifiek te zijn. Voor sommige toestellen moet de productiefase benadrukt worden. Voor andere toestellen dient de klemtoon te liggen op recyclage.

- In het geval van elektronische en elektrische producten die niet langer geschikt zijn voor herfabricage, zijn de locatie van de recyclage- en afvalverwerkingsfaciliteiten alsook het bepalen van het niveau van recycling van vitaal belang voor het reduceren van hun impact op het milieu.

- In mathematische modellen voor het ontwerpen van recyclagenetwerken waarin afval, energie en kosten geminimaliseerd worden, is een complete opsomming van de pareto-efficiënte oplossingen onmogelijk doordat hun aantal simpelweg te groot is. Wij stellen een eenvoudige methodologie voor om de beslissingnemer te helpen bij het kiezen tussen deze drie dimensies (i.e., afval/energie/kosten), en om het maken van trade-offs mogelijk te maken.

- Consumenten vragen hoge kortingen voor geherfabriceerde elektronische producten. De determinanten die deze kortingen drijven zijn nog steeds niet bekend. Wij vinden dat de aanwezigheid van externe referentieprijzen een significante impact heeft op de bovenvermelde kortingen. Een verder begrip van de factoren die de kortingen bepalen zou een belangrijke stap betekenen bij het verhogen van eco-efficiëntie binnen de elektronische sector.

Curriculum vitæ

João Quariguasi Frota Neto graduated, with *Summa Cum Laude*, from the Federal University of Ceará in Civil Engineering. Short after his graduation, in 1999, he joined a 2-year M.Sc. program in Operations Research and Operations Management, at the Instituto Alberto Luiz Coimbra de Pós Graduacão e Pesquisa em Engenharia (COPPE), Federal University of Rio de Janeiro[1]. During his bachelor and master studies, he was also a recipient of the CNPq fellowship from the Brazilian Ministry of Science and Technology. From 2003 to 2004 he lectured at the University of Fortaleza.

In October 2004 he became a full time Ph.D. candidate at the Rotterdam School of Management, Erasmus University. During his Ph.D. studies, he visited the Technical University of Braunschweig, where he worked with Professor Thomas Spengler and dr. Grit Walther.

He has presented his work in many international conferences, such as the meetings of the Production and Operations Management Society (POMS), the international meetings of the Production and Operations Management Society (POMS international), the European Conference on Operations Research (EURO). He also presented

[1]Since 2000, at the University regained the right to be called also "Universidade do Brasil"

his work in the workshop on reverse logistics held by the Vanderbilt University. Furthermore, he has papers accepted or published in numerous international journals: *Journal of the Operations Research Society*, *International Journal of Production Economics*, *European Journal of Operational Research*, *Journal of Jiaotong University*, and the *Journal of Manufacturing Technology Management*. He has also served as a reviewer for the *European Journal of Operational Research*, *International Journal of Production Economics* and *Decision Support Systems*.

Since September 2008 João lives in Leeds. He works as a Lecturer in Operations Management at the Bradford School of Management.

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Consumers, NGOs and governments have acknowledged the potential threat posed by these electrical and electronic products. They have systematically demanded companies to reduce the environmental impact caused by their products and services. Companies have responded to these pressures and have engaged in a number of environmentally friendly initiatives.

This thesis is motivated by the task of reducing the environmental impact caused by the myriad of electrical and electronic products that make our lives more comfortable and enjoyable. More specifically, it addresses the challenge of efficiently and effectively mitigating such impacts.

We show that companies will need a mixture of strategies to respond to this challenge. Furthermore, we show that these strategies must consider environmental, technical and marketing aspects of the business of electrical and electronic products. These three aspects need to be considered systemically, and the solutions will vary greatly according to the companies, the products they manufacture, and the ways in which their supply chains are organized.

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