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From closed-loop to sustainable supply chains: The WEEE case

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Abstract

The primary objective of closed-loop supply chains (CLSC) is to improve the maximum economic benefit from end-of-use products. Nevertheless, literature within this stream of research advocates that closing the loop also helps to mitigate the undesirable environmental footprint of supply chains. Therefore, closed-loop supply chains are assumed to be sustainable supply chains almost by definition. In this paper we analyze if and when this assumption holds. We illustrate our findings based on the supply chain of Electric and Electronic Equipments (EEE). For all phases of the supply chain, i.e. manufacturing, usage, transportation and end-of-life activities, we assess the magnitude of environmental impacts, based on a single environmental metric, namely Cumulative Energy Demand (CED). Given the environmental hot-spots in the Electric and Electronic Equipments supply chain, we propose useful extensions for existing CLSC optimization models to ensure that closed loop supply chains are at the same time sustainable ones.

1 Introduction

Managing closed-loop supply chains (CLSC) is a research area that received increasing interest among academic researchers and society in recent years. We refer to closed-loop supply

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chains as those supply chains where is taken care of items once they are no longer desired or can no longer be used (Flapper et al. [2005]). Increased legislation in the field of producer responsibility, take-back obligations and setting up collection and recycling systems leads to a strong focus on CLSC management. In the European Union, legislation concerning the waste of electrical and electronic equipment (WEEE) has mandatory collection and recycling objectives since 2005 (see Savage [2005]). WEEE-alike legislation has also been introduced in Canada, Japan, China and a number of states in the US. Apart from environmental drivers (voluntarily or forced by legislation), it is sensible to believe that the economic agents within the supply chain aim at reaping the maximum benefit from the reverse part of the supply chain, as expected in any economic activity. The benefits are direct, i.e. profiting from re-selling, re-furbished equipments, spare parts or virgin material (Fleischmann et al. [2000]). Returned products often contain value to be recovered in one way or another.

Sustainable supply chains are not clearly defined yet. A popular definition states that sustainable supply chains require coordination of social, environmental and economic dimensions (the triple bottom line), see e.g. Matos and Hall [2007]. Closing supply chains is regarded as environmentally friendly, in casu sustainable. Taking care of end-of-use items instead of disposing them, is assumed to be a proven measure to improve sustainability of supply chains (Geyer and Jackson [2004]). A major assumption underlying take-back legislation is again that recycling and recovering larger quantities of materials will lead to a reduction of environmental impacts.

Literature from the last decade provides quite some examples of good alignment between business and the environment in supply chains (e.g. Rao and Holt [2005]). In these examples closing the loop yields environmental gains even if business economics is the main driver (Guide and Van Wassenhove [2003], Guide et al. [2003]). Situations where business and the environment objectives are perfectly aligned are called “win-win”, “double-dividend”, “free-lunch” (Orsato [2006]), or “low hanging fruit” situations. On the other hand, studies are known where trade-offs do occur between what is economically rational in the supply chain and what is sustainable for the population as a whole (e.g. Walley and Whitehead [1994]). Integrating sustainability in supply chain models does increase the complexity of the models a lot (Matos and Hall [2007]). This seems more urgent in a trade-off situation than in a win-win situation. Therefore, an interesting question is: can we differentiate between the win-win situations and the trade-off situations in this field? In this paper we will analyze if and for which cases the assumption of a sustainable closed-loop supply chain does hold. We will discuss circumstances where the assumption is not fulfilled.

We will focus on two main questions: (i) which action is best to improve the environmental footprint of the closed loop supply chain (e.g. recycling, remanufacturing, product design)? and (ii) how can CLSC models be extended to represent the trade-offs between environmental and economic benefits in the supply chain? The answers to both questions will attribute to ensure that closed loop supply chains are at the same time sustainable ones. In section 2, we elaborate further on the concept of sustainable closed-loop supply chains. If decision makers intend to improve the environmental performance of the supply chain, they first need to investigate the environmental impacts in the various life cycle phases of the products. As soon as the critical life cycle phases are known, measures can be taken to improve sustainable performance. In section 3, we discuss the contribution of CLSC models to the sustainability of the supply chain. In section 4, we analyze five products covered by the European Directive on Waste Electrical and Electronic Equipment (EU [2003]), namely a a PC, a mobile phone, a TV set, refrigerator, a washing machine. We estimate the environmental impacts for the various life cycle phases of these products. Section 5 suggests extensions to improve the sustainability of the closed-loop supply chain. Section 6 exemplifies such extension using the remanufacturing lotsize problem as a starting point. Finally, in section 7 the main conclusions are summarized.

2 The sustainable (closed-loop) supply chain concept

Sustainability is not yet operationalized in Operations Management literature. The most used definition is "using resources to meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED [1987]). This definition is rather abstract and raises more questions than answers. Linton et al. [2007] transfer the concept of sustainability to supply chains and state that: A sustainable supply chain is a supply chain integrating issues and flows that extend beyond the core of supply chain management such as product design, manufacturing by-products, product management during use, product life extension and recovery processes at end-of-life. Figure 1 represents a general framework for a sustainable (closed-loop) supply chain.

(insert Figure 1)

A supply chain considers the product from initial processing of raw materials to delivery to the customer. Therefore, main activities in the supply chain are raw material extraction, manufacturing and usage (the forward chain in Figure 1). As stated by Linton et al. [2007], a number of processes can be added in order to become sustainable such as product design, product management during use, product life extension and recovery processes at end-of-life. Recovery processes (as described by Thierry et al. [1995]) include reuse, testing, repairing, disassembling, refurbishing, remanufacturing, recycling and energy recovery (the reverse chain in Figure 1). Transportation takes place in both the forward and reverse part of the supply chain. In this paper, we acknowledge that extending a supply chain with regard to reverse logistics processes is an important issue for sustainable supply chains. However, in literature many authors assume that adding reverse processes and closing the loop is directly leading to a sustainable supply chain. We do not agree with this view and state that these processes might be necessary to become sustainable, but that just adding processes does not make a supply chain sustainable by definition. Sustainability, in our view, can only be obtained by changing the objectives from economy driven towards economy, environment and society driven. This means that multiple objectives in a CLSC model are necessary if there is a clear trade-off between economic and environmental objectives. However, this often makes the model much more complex.

Against this background, the interesting questions are: Which processes should be added for the supply chain in order to become a sustainable one? Are there differences among products? Can we differentiate between the win-win situations and the trade-offs situations in this field? Are there settings, where economic and environmental objectives are perfectly aligned, and therefore it is reasonable to maximize economic benefit from end-of-use products? Which existing models are pointing in a sustainable direction, and which models have to be extended in order to account for all aspects that are important when aiming at sustainable development?

In order to answer these questions, we will first analyze existing closed loop supply chain models, and then exemplarily analyze products these models are applied to.

3 Sustainability of CLSC models

Rubio et al. [2006] analyze 10 years of research in reverse logistics, product recovery and closed loop supply chains and show that currently almost all CLSC models are cost-driven, i.e. have economic drivers as main objective. We will analyze CLSC models for possibilities to lead into a sustainable direction. Based on the classification by Dekker et al. [2004], three categories of models are distinguished, i.e. management of recovery and distribution of end-of-life products, production planning and inventory management, and supply chain management issues in reverse logistics.

3.1 Management of recovery and distribution of end-of-life products

This group of models analyzes the different physical flows relating to the collection and distribution of end-of-life (EOL) products. Models are either focusing on distribution or on disassembly and recycling, or are combining both aspects.

Transportation is undoubtedly a significant source of costs in the supply chain. Not surprisingly, routing models are a popular class of OR formulations regarding the design of supply chains. The same holds for the design of reverse logistics systems, where Vehicle Routing Models and Facility Location Models are also applied. With regard to modeling of disassembly and recycling processes, the aim with end-of-life products is mainly to generate standardized material fractions like metals or plastics that can be sold on the market. Examples of models for end-of-life products combining transportation and recycling processes can be found in Spengler et al. [1997] and Jarayaman et al. [1997].

This class of models is mainly based on economic evaluation. In most cases, the aim is to design and manage a recycling/recovery system with minimal transportation and processing costs. With regard to disassembly, the assumption is mainly that recycling of a material is sustainable per definition, and thus that ecological impacts can be neglected.

3.2 Production planning and inventory management

In this category, models combine reverse processes with the traditional forward supply chain processes, i.e. remanufacturing, reuse, and refurbishing. These processes can extend the life span of a product. Quantitative models on design and management of remanufacturing systems are reviewed in Thierry et al. [1995] and Gungor and Gupta [1999]. An important decision problem in this category of models is which parts to disassemble for reuse opportunities. This question has long been studied in the mainstream of CLSC, see Lambert [2003]. Deterministic and stochastic models where parts out of disassembled products are re-used for production of new products are described by a.o. Guide et al. [2000], Bayindir et al. [2003] and Inderfurth [2004].

Two important aspects have to be noticed when looking at the current planning approaches. First, most authors assume that extending the lifetime of a product is sustainable per se. Thus, most models for design and manufacturing of remanufacturing systems take into account economic criteria and ignore environmental impacts. This holds also for disassembly models. These models aim at the question, which components to disassemble in order to support the remanufacturing process. Questions regarding which of the components or products to re-use aiming at ecological objectives are mostly neglected.

3.3 Supply chain model issues in reverse logistics

The topic "supply chain management issues in reverse logistics" concerns those works analyzing the strategic decisions which a reverse flow of end-of-life products generates in the management of the supply chain. Rubio et al. [2006] mention that this class has more qualitative papers than quantitative ones. Models can be found concerning the impact of environmental regulation and the environmental management of reverse logistics. This class of papers only grew to a substantial level since the year 2004. Bufardi et al. [2006] study the selection of alternatives for treating a product at its end of life based on economical, environmental and social criteria. The paper proposes a multicriteria decision-aid (MCDA) approach to aid the decision-maker in selecting the best end-of-life alternatives. Walther and Spengler [2005] estimate the impacts of new legal regulations on the supply chain of electrical devices. They stress the importance of the optimal disassembly depth and sequence of discarded products for the optimal recovery decision. Krikke et al. [2003] use a multi-objective optimization model with three criteria: network costs, energy use, and waste volume. The model optimizes the forward and reverse logistics for a refrigerator supply chain network, and optimal design choices for the refrigerator.

These types of recent models look very promising for including sustainable issues. The presented models are normally applied to complex products, e.g. electrical products (an exception are the distribution and recycling models that are also applied to materials like sand or carpets). Therefore, we analyze the environmental impact of such complex products exemplarily within the next section.

4 Environmental impacts of electrical and electronic equipment

Awareness of the environmental impact of products is a recent trend. This trend has fostered a number of analyses on the environmental impacts of consumption in European households. Supermarkets label their products with environmental foodmiles, firms invest in communicating the environmental impacts of their products (e.g. "Greening your Apple"), etc.

The Electronic and electrical product category appears as a large source of environmental footprint (Tukker et al. [2005]). The production and usage of washing machines, refrigerators and freezers, telecommunication devices, audio and video equipments are responsible for approximately 8% of the overall generated global warming potential in a household. Labouze et al. [2003] show that electric equipments are responsible for 10% to 20% of the overall environmental impact on the categories depletion of non-renewable sources, greenhouse effect, air acidification, years of lost life, and dust.

Closing the supply chain is advocated to mitigate the environmental impact of the electric equipments our society consumes. Studies like Labouze et al. [2003] and Mayers et al. [2005] calculate the environmental impact of a product using a list of various environmental impact indicators, such as human toxicity, ecotoxicity, photochemical oxidation, acidification, ozone layer depletion etc. Mayers et al. [2005] conclude in their study that the targets of the WEEE legislation could easily lead to mixed results from a life cycle perspective. Some environmental impacts decrease while others increase. Furthermore, WEEE legislation targets have no incentive to adapt the design of products, improving the environmental impacts in an earlier stage of the life cycle.

We analyze the magnitude of the environmental impact using a single measure of environmental impact: Cumulative Energy Demand. This measure aggregates other environmental indicators in terms of energy demand. Recent studies show a high correlation between this indicator and the widely accepted Eco-indicator 99 (Helias and Haes [2006]). The result is also quite robust for the disaggregated environmental impact indicators, i.e. resource depletion, marine toxicity, etc. (Helias and de Haes [2006]). Walk et al. [2005] finds an overall Spearman correlation of $\rho = 0.94$ between the CED measure and the aggregated Eco-indicator results, as well as individual impact correlations ranging from $\rho = 0.73$ to $\rho = 0.96$. The environmental impact estimations are collected for a personal computer, a mobile phone, a refrigerator, a tv and a washing machine. The results are based on secondary data and environmental impact databases (Buwal [1998]).

4.1 Environmental impacts of personal computers and mobile phones

Computers have become common appliances in households. 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, the life cycle of computers has drastically diminished during the last twenty years, causing large amounts of computer waste all over the world. End-of-use computers, if not properly treated, may cause serious threats to human health. Recently, developed countries have been accused of exporting computer waste to places with looser environmental control instead of providing a proper end-of-life treatment for such products. Greenpeace has reported such abuses and launched the campaign "Hi-Tech: Highly toxic" (Greenpeace [2006]).

Comprehensive results on environmental impact of computers are scarce. We base our analysis on the results obtained by Williams [2005], which are align with the results by Gotthardt et al. [2005]. Although the production phase yields most of the environmental footprint, reclaiming such burdens via traditional bulk recycling is hardly possible. The reason for such apparent paradox lies in the embedded computer's semiconductors: the majority of the energy is used to produce the semiconductors, and very little can be claimed back via bulk recycling. This observation has direct implications for the WEEE and WEEE-alike legislation, where the targets are set in obligatory percentages of collection and recycling. Note that the environmental impacts due to the transportation phase are hardly relevant compared to the complete lifecycle impact. However, the impact of transportation depends heavily on the assumptions of where the parts, components and computers are assembled. For desktop computers, Williams and Sasaki [2005] calculate that transportation can in an extreme case consume up to 8% of the energy needed over the entire life cycle of the product. The CED distribution for the production, including assembling, transportation, and usage phase in a no loop supply chain is represented in Figure 2.

The results for mobile phones resemble those for computers. Gotthardt et al. [2005] results show that the production phase counts for approximately 60% of the overall environmental impact, excluding transportation. Again the environmental impact contribution of bulk recycling is irrelevant. The reason for the high share of manufacturing in the energy consumption of mobile phones seems again to lie in their embedded electronic pieces, such as printed circuit boards (Scharnhorst [2006]).

(insert figure 2)

Based on this figure, we conclude that extending the life time is a sensible way to improve the environmental impacts of computers and mobile phones. Doubling the life span of a PC from two years to four years would render a reduction of approximately 31% in the overall environmental impact. This is an important observation as design for extending the lifespan of a product is not rewarded in current legislation. Little energy can be claimed via bulk recycling, but a substantial amount can be reclaimed via reusing of components and equipments and refurbishing or remanufacturing of old electronic equipment. These results align with those found in Ruediger [2005].

4.2 Refrigerators, washing machines, and TV sets

Household refrigerators and freezers are large contributors to the environmental impact of electric and electronical equipment (EEE). For a refrigerator, 1,330 kg of fossil fuel is consumed to produce and use a refrigerator, of which 96% is consumed during the usage phase (Kuehr [2003]). Note that these data are already normalized to per year of lifetime. For a washing machine the results for CED are also aligned with those found for refrigerators. The energy required for the usage phase is approximately $\frac{3}{4}$ of the overall required energy for the whole life cycle (Rudenauer et al. [2005]). Watching TV is also an energy consuming activity. The energy consumption profile of a TV is close to that of the refrigerator. The usage phase for the TV is responsible for 89% of the overall CED (Behrendt et al. [1997]). The CED distribution for production, transportation and usage is presented in Figure 3.

The results for electric equipments as washing machines, refrigerators and TV sets show that environmental impacts are concentrated in the usage phase. Little improvements in terms of energy can be obtained via the adoption of better end-of-life decisions. This observation must be interpreted with care. The claim is not that bulk recycling will not improve the overall environmental performance of the aforementioned electric equipment. However, decreasing energy consumption during usage by new product innovations will inevitably have a positive effect on the environmental impacts too.

The examples in this section show that recycling materials as such may not be the most sustainable action. Improving environmental footprint means making ecologically intelligent decisions both in product design, product use and product recovery. In the next section, we focus on integrating the sustainable supply chain thinking into CLSC models.

5 Integrating sustainable supply chain issues in CLSC models

In this section, we explore the possibilities to include sustainability issues in CLSC models based on the results of section 3 and 4. Eventually, we present an approach for integration of supply chain issues into CLSC management.

5.1 CLSC models over the life cycle

The results of Sections 3 and 4 as well as conclusions that can be drawn from these results are visualized in Table 1. Section 4.1 showed that for the category computers and mobile phones the energy demand of the production phase dominates the energy consumption during usage. For these products, extension of lifetime will therefore reduce energy consumption per unit of time. As can be seen in Table 1, the most attractive alternative for reducing environmental impact of such equipment is therefore increasing the lifespan by strategies like repair, refurbishing and remanufacturing. Doing so, production of new equipment can be reduced, and thus the energy needed for the production phase is saved (column "production" in Table 1). Simultaneously, the amount of waste from end-of-use equipments is reduced, which also leads to a decrease in eco-toxicity and human toxicity.

Looking at section 4.2 it appears to be very product specific to conclude that adding on lifespan is entirely environmentally friendly, since some aging equipment are known to be more energy consuming than new ones. Based on the examples in Section 4, it seems to make more sense to refurbish computers than to refurbish TV sets. For products like TV sets and washing machines, it seems to be crucial to save energy during the lifetime (see column "manufacturing" in Table 1). However, as soon as products are sold, the manufacturer can no longer influence energy demand. Therefore, measures already have to be taken during the design phase of the product. Thus, the influence of reverse logistics is limited for these products. As soon as new energy-saving equipment is on the market, remanufacturing strategies might even contradict sustainable aspects.

Regardless whether the lifetime of a product is extended or not, at the end of its useful life each product needs to be recycled. New legal requirements like the WEEE directive focus on this step. The main aim in recycling end-of-life equipment is to recycle materials like metals and to properly treat harmful substances like lead or polychlorinated biphenyls. With regard to these topics, there are important decisions that have to be taken (column "recycling"). However, for products like the computer or mobile, the proportion of virgin material and energy that can be reclaimed by recycling processes is very small compared to the potential amendment with remanufacturing. This means that for some (but not all) products recycling should only be the last alternative after a long life. It seems to be necessary to shift the point of view of the legal measures with regard to these results.

(insert table 1)

5.2 Integrating supply chain models issues in reverse logistics

Based on these results, it can be shown that all of the models discussed in section 3 are justified from an environmental point of view. However, it also becomes clear that it is not sensible to apply all of the models to every product, and it can even be counterproductive to extend the supply chain with regard to all processes presented by Linton et al. [2007]. Against this background, we think that supply chain model issues have to be implemented into reverse logistics thinking in order to guarantee not only economic but also ecological viable results. Thereby, the classical reverse logistics models as presented in sections 3.1 and 3.2 are one important part and should be integrated. However, other approaches like Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have to be added, and some of the reverse logistics models are to be extended in order to consider not only economic but also ecological aspects. Therefore, we present an integrated approach in the following sections.

5.2.1 Obtain Life Cycle Data with help of LCA/LCC

The first prerequisite for an integration of supply chain thinking is that economic as well as ecological impacts of a product over its complete life-cycle are known as soon as possible, i.e. ex-ante in the design phase. In order to obtain environmental information, Life Cycle Assessment [DIN EN ISO 14.040 et sqq.] has to be carried out. Since this can be a very time-demanding and costly task - especially for complex products - generalized data for certain product types available in data bases (Buwal [1998]) or streamlined/simplified LCA approaches (e.g. Weitz et al. [1996]) can be used. Thereby, it seems not to be important to get very detailed information, but rather to get the overall picture. The same holds for Life Cycle Costing (Asiedu and Gu [1998]). By gathering information on the economic impact over the whole life cycle, the manufacturer gets information on economic trade-offs between life cycle phases.

5.2.2 Realize measures in the design stage of a product

As soon as data on the life cycle are known, improvement measures should be taken. As results of section 4 show, starting to green a supply chain within the reverse logistics phase is too late. Manufacturers have only limited influence on the usage phase of products and even on the recycling stage, but high potentials for conducting environmental improvements can be found within the design phase. Thus, if environmental and economic information is available very soon, measures can be taken in the design stage already. For products like washing machines, energy saving design might be an option (Behrendt et al. [1997]). If based on LCA, this information can even be used for marketing purposes (DIN EN ISO 14.040 et sqq.), e.g. by printing this information on the product label. But not only the future usage phase can be improved within the design stage of a product, but measures can also already be taken with regards to future remanufacturing and recycling processes. E.g. it might be reasonable to mark the used plastics in order to allow for recycling, or it might be feasible to reduce the diversity of screws used within the production phase in order to reduce the time needed for disassembly within the recycling phase.

From an LCC point of view, measures in the design stage might at first glance cause higher costs, e.g. higher costs in production, but might then result in lower costs during remanufacturing. The same holds for LCA results. Thus, profitability and environmental advantageousness of such measures becomes only clear if the whole life cycle is taken into account. The prerequisite for design for remanufacturing/design for recycling measures is an adequate anticipation of future remanufacturing and recycling processes. This can be done applying disassembly models ex-ante. Doing so, problematic materials for recycling, challenging connections, or harmful substances can be detected.

5.2.3 Realize the reverse logistic measures that are economically and ecologically feasible

In later life cycle phases of the product, realize only reverse logistic measures that are economically and ecologically viable. For some products, it might not be sensible to extend the lifetime, while at the end of the useful life of a product it is always important to focus on harmful and scarce substance.

(a) Apply classical reverse logistics models if economic and ecological results are align. If applied to the right products and the right life cycle phases, the models described within section 3.1 and 3.2 can be integrated in this step. The application of distribution and recycling models is mainly needed during the recycling stage as shown in the column "recycling" in table 1. As long as only transportation processes are to be optimized, straightforward economic driven distribution models will be sufficient in almost all cases. For example, routing models aim at the reduction in transportation kilometers (business objective), which is in turn directly correlated to reductions in the fuel consumption (environmental objective). However, as soon as the focus is on scarce and harmful substances, economic objectives are not sufficient any more. In recycling, it can be important to remove harmful substances even though it is not economically feasible to do so. The trade-offs between environment and profit might even increase if distribution and recycling is looked at with integrated models. It might be the case that transportation increases because of higher recycling, since recycling facilities are often further away than land-filling sites (Walther and Spengler [2005]). With regard to these results an extension of disassembly models, which can easily be transferred to integrated distribution and disassembly models, is presented in paragraph b). For products with high impact in the production stage (column "production"), integrated production planning and inventory management models are important in order to apply remanufacturing strategies. As shown in section 3.2, measures like refurbishing, remanufacturing or reuse are often economically viable. Purely economic models seem to be sufficient - but only if applied to the right products (see section 4). However, in order to answer the question which components to reuse, trade-offs might occur. The consequence of purely economic criteria can be that components with high environmental and low economic yield will not be recovered and likely end up in bulk recycling with little or no environmental reclamation. Therefore, the disassembly models in the integrated production planning and inventory management models should be extended with regard to environmental criteria. We will show such an extension in section 6.

(b) Extend the classical models if there is a trade-off between environment and profit. Based on the examples studied, the risk of losing environmental gain by one-dimensional economic optimization is substantial as soon as trade-offs between ecological and economic issues occur. Therefore, some models have to be extended to multiple objective models. As shown above, disassembly planning is a core approach when aiming at sustainable supply chains for complex products. First, ex-ante optimization of disassembly is already helpful for improvements within the design stage of a product. Second, disassembly models are necessary in order to determine the components to be remanufactured and reused when extending the lifespan of a product. Doing so, functionality of products and parts can be recovered, and thus environmental impacts like resource depletion and greenhouse gas emission can be reduced. Third, it is also necessary to determine optimal disassembly depth and material fractions to be generated during the recycling stage aiming at the removal of harmful substances and gaining of scarce materials at the end of the useful life of a product. However, when looking at disassembly models, the optimal economic disassembly decision is not necessarily the best solution for the environment: components with high potential environmental gains and low profit margin are left in the original equipment to be recycled or directed to landfill. Therefore, these models are to be extended with regard to environmental objectives.

6 Application of the framework: Eco-efficient lotsize with remanufacturing options

In this section, we use the example of the efficient lotsize with remanufacturing options to illustrate how to integrate sustainable supply chain issues in CLSC models.

The economic lotsize model is a classic problem in Operations Research (a review can be found in Brahimia et al. [2006]). Variants of the classic model which incorporate remanufacturing decisions have been proposed in Golany and Yang [1998], Beltran and Krass [2002], Teunter et al. [2006] Choi et al. [2006]. In a nutshell, the objective in these models is to determine how many items should be manufactured and remanufactured, and to define in which periods manufacturing and remanufacturing should take place. We will illustrate how this problem can be extended to incorporate sustainable dimensions. We assume that computers are the items to be produced.

In this section, we use the model described in Golany and Yang [1998] as our start. Golany and Yang [1998] consider a single-item production system which faces periodic deterministic demand over a finite horizon. The demand can be fulfilled by either manufactured or remanufactured products. The demand is known for the entire planning horizon. Furthermore, backlogging is not permitted. The production, holding for both used and new items, remanufacturing, and disposal costs are known for each period. The following definitions are used in the aforementioned paper.

- B_t: Number of used items newly available in period t;
- D_t: Number of new items demanded in period t;
- x_t: Number of newly produced items in period t;
- y_t: Inventory of new items held at the end of period t (y_0; y_T are externally given);
- z_t: Number of used items being remanufactured in period t;
- u_t: Inventory of used items at the end of period t (u_0; u_T are externally given);
- v_t: Number of disposed items in period t;
- $P_t(x_t) \geq 0$ Production cost in period t;

- $H_t(y_t) \geq 0$ New-item holding cost in period t;
- $R_t(z_t) \geq 0$ Remanufacturing cost in period t;
- $W_t(u_t) \geq 0$ Used-item holding cost in period t;
- $S_t(v_t) \geq 0$ Disposal cost in period t.

The objective is to minimize costs, given by:

$$min \sum_{t=1}^{T} P_t(x_t) + \sum_{t=1}^{T} H_t(y_t) + \sum_{t=1}^{T} R_t(z_t) + \sum_{t=1}^{T} W_t(u_t) + \sum_{t=1}^{T} S_t(v_t) \quad (1)$$

The following constraints ensure material conservations.

subject to

$$x_t + y_{t-1} + y_t + z_t = D_t \quad \forall t = 1, ..., T \quad (2)$$

$$z_t + u_t - u_{t-1} + v_t = B_t \quad \forall t = 1, ..., T \quad (3)$$

$$xt, y_t, z_t, u_t, v_t \geq 0 \quad \forall t = 1, ..., T$$

6.1 Integrating sustainable supply chain issues in the lot size problem

As we have shown in Section 4, most of the energy used in the life cycle of a computer is demanded by manufacturing. Given the results in Section 4, an effective way to reclaim energy is therefore to increase the levels of remanufacturing. For the problem in question, a deviation from the optimal economic economic solution may show a potential for a significant decrease in the total CED. The CED is expressed as:

$$min \sum_{t=1}^{T} E_x(x_t) + \sum_{t=1}^{T} E_z(z_t) \quad (4)$$

It is important to say that the proposed extension of the model is sensible for the application with computers, but not necessarily with other electrical and electronic products.

The proposed extension of the lot size problem is a bi-objective linear problem. Solving a multi-objective problem is, in general, a more complex task than solving its single objective counterpart. One of the difficulties in addressing problems with multiple objectives is to determine what precisely is the solution sought. In broad terms, solving a multi-objective problem involves the following steps (i) identifying the solutions that are not dominated, (ii) capturing the decision maker preference, or eliciting 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 and 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 Multi-objective Programming (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]).

6.2 The solution approach

In the previous section we reviewed the main methodologies in multi-objective programming. In this section we advocate the characterization of the efficient frontier for the problem we intend to solve. More specifically, we intend to characterize the Pareto efficient frontier. Such characterization allows us to determine the trade-offs between the resulting environmental impacts and costs.

In order to find the efficient frontier, we use the software ADBASE 5.1 (Steuer [1988]). Assuming that manufacturing is more expensive than remanufacturing and that holding new items in inventory is more expensive than holding used items, we assign the following values to the cost parameters: $P_t = 200$, $H_t = 60$, $R_t = 150$, $W_t = 50$, S_t=20, $\forall t = 1, ..., T,$. The energy to manufacture a computer is E_x=5000, and to remanufacture E_z=500. Then, we solve the model for 60 demand scenarios where the demand and the number of returned items are randomly generated between 0 and 100. Furthermore,T=16. The statistics for the number of extreme efficient points is presented in Figure 4 for 60 randomly generated problems.

(insert figure 4)

Figure 5 exemplifies the efficient frontier, regarding costs and environmental impact, from a problem with the following parameters:

$$P_t = 200,\ H_t = 60,\ R_t = 150,\ W_t = 50,\ S_t{=}20,\ \forall t = 1, ..., T,$$

Ex=5000, Ez=500 and

D_t=72,70,94,67,71,50,85,86,97,66,98,53,73,54,77,94

B_t=51,57,77,92,68,81,96,73,89,56,80,79,64,87,92,59

(insert figure 5)

The inventory for each of the extreme efficient points presented is Figure 4 is represented in Figure 6.

(insert figure 6)

As Figure 4 points out, the eco-efficient remanufacturing model results in some different efficient points. Therefore, the preferences of the decision maker are really important to come to a preferable eco-efficient solution. Figure 5 and 6 show that the extreme efficient solution H (minimize costs) really differs with the extreme efficient solution A (minimize CED), both in objective values as in inventory patterns. This confirms our statement that the classical models should be extended if there is a trade-off between environment and profit.

The example illustrates the added value of incorporating sustainable supply chain issues in CLSC models. First, it becomes obvious that many extreme efficient solution points exist. This gives the decision maker more insight in the decision space he has. Second, integrating sustainable supply chain issues in CLSC models provides the possibility to estimate the potential gain in environmental improvements compared to the costs needed to obtain this gain (Figure 5). This helps in deciding on the most interesting measures to take. Finally, Figure 6 illustrates the implications of choosing one extreme point over the other in terms of production and inventory processes.

Regarding the CPU-time necessary to solve the proposed formulation, general results from MOLP suggest that the number of extreme efficient points can become very large, making it impossible the complete enumeration of these solutions. Further research is needed, therefore, to determine if, for this particular formulation, it is possible to enumerate all extreme efficient points. Alternatively, approximations methods can be directly used, since these have been proved quite efficient in solving MOLP (see e.g. Fruhwirth et al. [1989], Liu et al. [1999], and Fernandez and Toth [2007]).

7 Conclusions

Some ten years ago we witnessed a hot discussion between those advocating environmental improvement as a driver of competitive advantage (Gore [1991], Porter and Vanderlinde [1995]) and those advocating that substantial improvements for the environment are only achievable via substantial investments with little or no direct return (Walley and Whitehead [1994]. This discussion is moving towards the search for win-win situations, and solutions with good trade-offs. If decision makers want to improve environmental performance of the supply chain, they first have to take into account the environmental impacts occurring within the various life cycle phases of the products. As soon as the critical life cycle phases are known, measures can be taken more effectively to improve sustainable performance. Based on the Electric and Electronic Equipment case we can conclude the following:

- Transportation does not appear to be significant for the overall environmental impact, despite its appealing win-win nature.

- Supply chains with a high share of manufacturing in the energy consumption gain by extending the lifespan of the product. Bulk recycling is not a good option here, or at least should be the last option after a long life. Adoption of re-use, re-manufacturing and re-furbishing activities appears to positively impact the sustainability of the chain. This can be qualified as a trade-off situation where models for disassembling decisions have to be extended with the issue of product-life extension.

- Supply chains with a high share in energy consumption gain by improving the product design and product management during use. Here both win-win situations and trade-off situations occur. Less energy during the use phase saves money, thus creating a win-win situation. Environmentally conscious product design might be expensive at the start of the product life but saves money during the disassembly phase, thus creating a trade-off situation.

- Before extending closed loop supply chains, first a life cycle analysis of the entire life of the product is necessary to and the environmental hot-spots in the supply chain.

Furthermore, in this paper we raised a number of issues regarding the transition from closed-loop supply chains to sustainable supply chains that have not been fully addressed by the existing literature. Concerning the networks of recovery of end-of-life products, for instance, where should remanufacturing facilities be located considering business and the environment? E.g. moving remanufacturing from Europe to the Far East may reduce costs, but it will also imply further transportation. Concerning the decision on what to remanufacture, how would this decision change in case not only profit, but also environmental impact is considered? What are the trade-offs between these two dimensions in this case? s there a difference between the remanufacturing for lease and remanufacturing for resale? Needless to say, for each of these questions, it is also necessary to examine the existing literature and to find a possible solution technique that can provide a solution for the questions. These are new interesting new venues of research, which we consider worth pursuing.

figures and tables

Table 1: Impacts on life cycle phase of Manufacturing,Usage and Recycling

Impacts on life cycle phase	Manufacturing	Usage	Recycling
Products	computer, mobile	TV set, washing machine	-
Recommendations	extend life time	decrease energy demand	focus on harmful and scarce substances
Options	reuse, remanufacturing, refurbishing, reuse spare parts	energy saving design	optimize recycling process
Models	disassembly models production planning	life cycle assessment life cycle costing	disassembly models distribution models

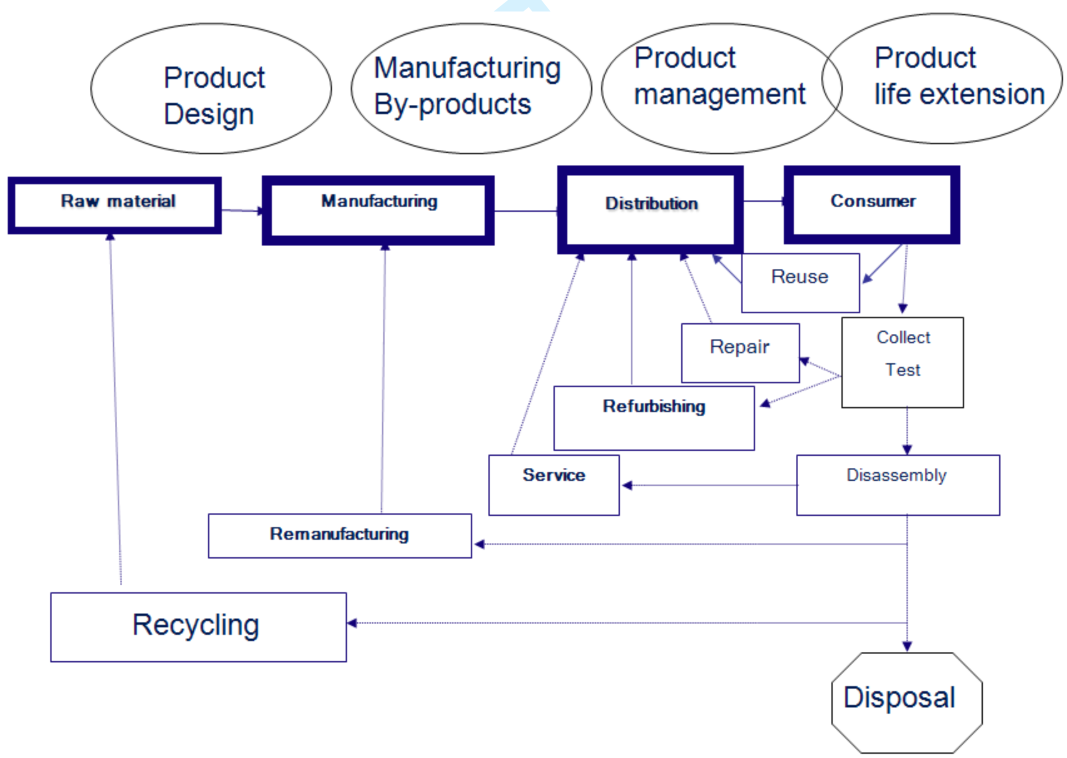

Figure 1: General frame for a closed-loop (sustainable) supply chain

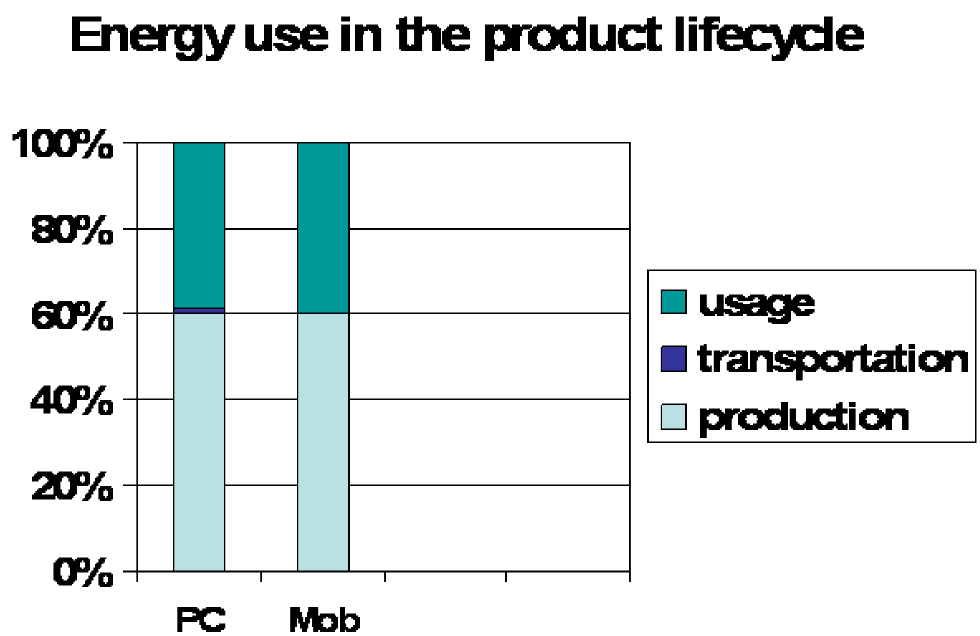

Figure 2: Energy consumption profile for PCs and mobiles

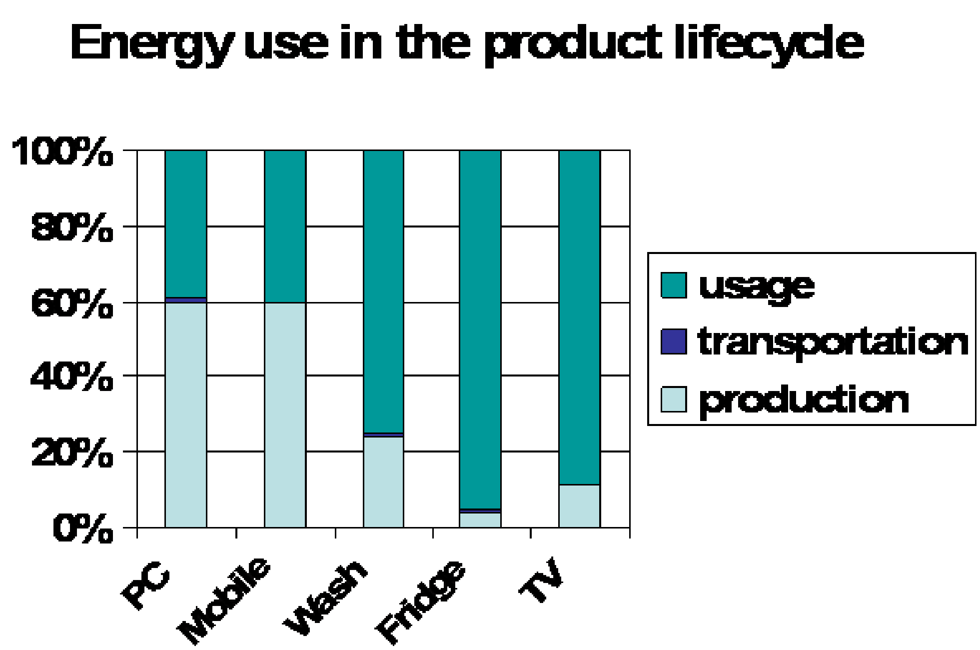

Figure 3: Energy consumption profile for PCs, mobiles, washing machines, fridges and TVs

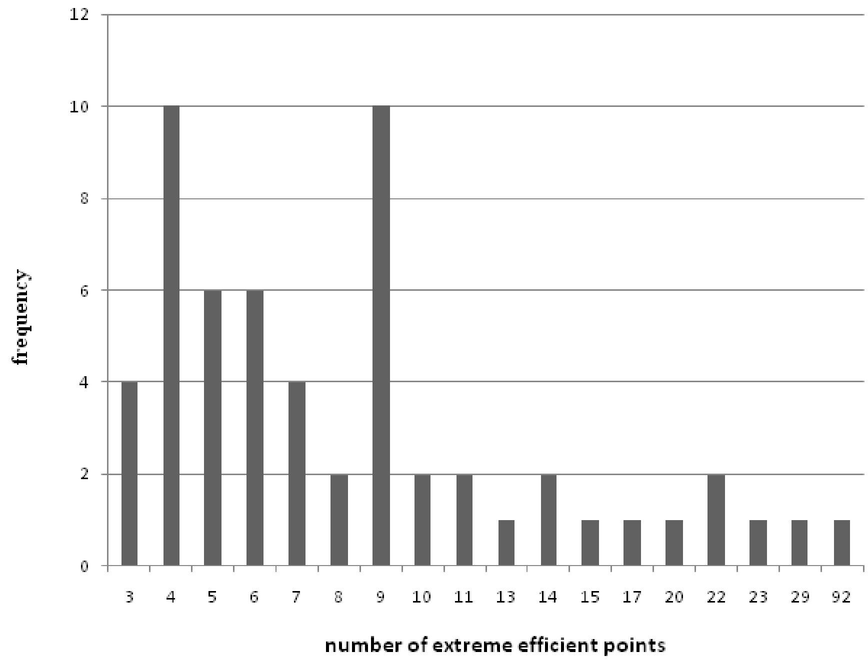

Figure 4: Number of extreme efficient points

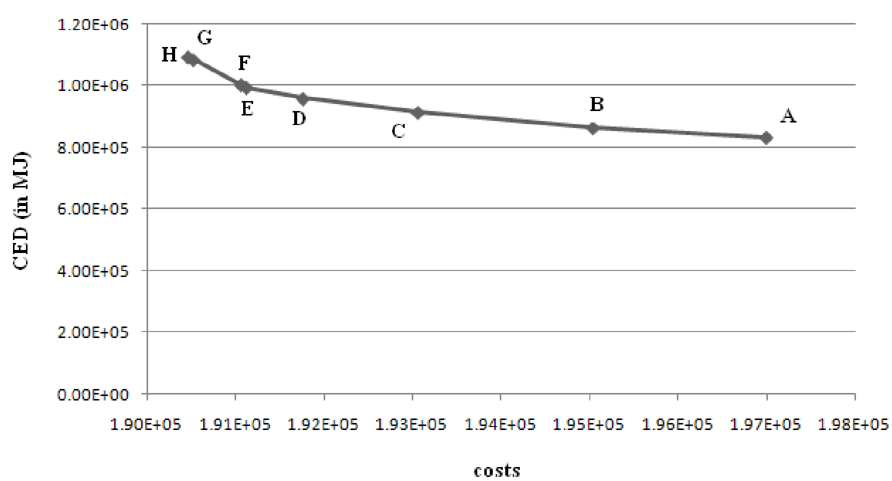

Figure 5: Pareto optimal frontier

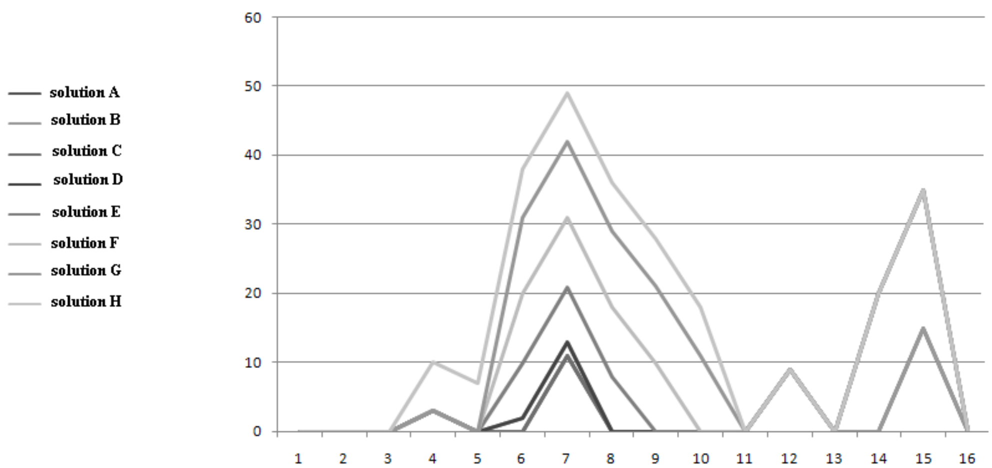

Figure 6: Inventories for the different solutions

References

Y. Asiedu and P. Gu. Product life cycle cost analysis: State of the art review. *International Journal of Production Research*, 36(4):883–908, 1998.

Z. P. Bayindir, N. Erkip, and R. Gullu. A model to evaluate inventory costs in a remanufacturing environment. *International Journal of Production Economics*, 81:597–607, 2003.

S. Behrendt, R. Kreibich, S. Lundie, R. Pfitzner, and M. Scharp. *kobilanzierung komplexer Elektronikprodukte*. Springer, Berlin/Heidelberg, 1997.

J.L. Beltran and D. Krass. Dynamic lots sizing with returning items and disposals. *IIE Transactions*, 34:437448, 2002.

J. Benayoun, J. Montgolfier, J. Tergny, and C. Larichev. Linear programming with multiple objective with multiple objective functions: Step method (STEM). *Mathematical Programming*, 8:366–375, 1971.

N. Brahimia, S. Dauzere-Peresb, and N.M. Najidc. Dynamic lot sizing with product returns and remanufacturing. *European Journal of Operational Research*, 168(1):1–16, 2006.

A. Bufardi, R. Gheorghe, D. Kiritsis, and P. Xirouchakis. Multicriteria decision-aid approach for product end-of-life alternative selection. *International Journal of Production Research*, 42, 2006.

Buwal. Life Cycle Inventories for Packagings, part 1 and 2. SAEFL, Bern, 1998.

V. Chankong and Y. Y. Haimes. *Multiobjective decision making: theory and methodology*. North-Holland, New York/Amsterdam, 1983.

B-C. Choi, Hang-Sik Shin, S-Y Lee, and T. Hur. Life cycle assesment of a personal computer and its effective recycling rate. *The International Journal of Life Cycle Assessment*, 11(2), 2006.

R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. van Wassenhove. *Reverse Logistics: Quatitative Models for Closed-Loop Supply Chains*. Penguin, Berlin/Heidelberg, 2004.

G. E. Evans. An overview of techniques for solving multiobjective mathematical programs. *Management Science*, 30(11), 1984.

J. Fernandez and B. Toth. Obtaining an outer approximation of the efficient set of nonlinear biobjective problems. *Journal of Global Optimization*, 38(2):315–331, 2007.

S.D.P. Flapper, J. A. E. E. van Nunen, and L. N. Van Wassenhove. *Managing Closed-Loop Supply Chains*. Springer, Berlin/Heidelberg, 2005.

M. Fleischmann, H. R. Krikke, R. Dekker, and S. D. P. Flapper. A characterisation of logistics networks for product recovery. *Omega-International Journal of Management Science*, 28 (6):653–666, 2000.

B. Fruhwirth, R.E. Burkard, and G. Rote. Approximation of convex curves with application to the bicriterial minimum cost flow problem. *European Journal of Operational Research*, 42:326–338, 1989.

R. Geyer and T. Jackson. Supply loops and their constraints: The industrial ecology of recycling and reuse. *California Management Review*, 46(2):55–73, 2004.

B. Golany and G. Yang, J. Yu. Economic Lot-sizing with Remanufacturing Options. *IIE Transactions*, 33(11):995–1004, 1998.

A. Gore. *Earth in Balance: Ecology and the Human Spirit*. Penguin, New York, 1991.

V. Gotthardt, A. Fudrini, M. Margni, O. Jolliet, P. Salina, A. Kuhn, and D. Singy. Company-LCA case study of Swisscom. Discussion forum, École Polytechnique Fédérale de Lausanne Swisscom, 2005.

V. D. R. Guide and L. N. Van Wassenhove. *Business Aspects of Closed-Loop Supply Chain*. International Management Series. Pittsburg,Pennsylvania, 2003.

V. D. R. Guide, V. Jarayaman, R. Srivastava, and W. C. Benton. Supply-chain management for recoverable manufacturing systems. *Computers & Industrial Engineering*, 30:125–142, 2000.

V. D. R. Guide, T. P. Harrison, and L. N. Van wassenhove. The challenge of closed-loop supply chains. *Interfaces*, 33(6):3–6, 2003.

A. Gungor and S.M. Gupta. Issues in environmentally conscious manufacturing and recovery products: a survey. *Computers & Industrial Engineering*, 36(4):811–853, 1999.

A. Helias and U. Haes. LifeCycle assessment and the use of broad indicators. *Journal of Industrial Ecology*, 10(3), 2006.

K. Inderfurth. Optimal policies in hybrid manufacturing/remanufacturing systems with product substitution. *International Journal of Production Economics*, 90:325–343, 2004.

E. Jacquet-Lagreze and J. Siskos. Assessing a set of additive utility functions for multicriteria decision-making, the UTA method. *European Journal of Operation Research*, 10(2):151–164, 1982.

V. Jarayaman, R. A. Patterson, and E. Rolland. The design of reverse distribution networks: models and solution procedures. *European Journal of Operational Research*, 150:128–149, 1997.

P. Korhonen and J. Wallenius. A pareto race. *Naval Research Logistics*, 35(6):615–623, 1988.

H. Krikke, J.M. Bloemhof-Ruwaard, and L. N. van Wassenhove. Current product and closed-loop supply chain design with an application to refrigerators. *International Journal of Production Research*, 41(16):3689–3719, 2003.

R. Kuehr. Managing PCs through policy: Review and ways to expand lifespan. In R. Kuehr and E. Williams, editors, *Computers and the Environment: Understanding and Managing their impacts*, pages 253–278. Kluwer Academic Publishers, 2003.

E. Labouze, V. Monier, and J-B Puyou. Study on external environment effects related to the life cycle of products and services. Final report, 2003.

A. J. D. Lambert. Disassembly sequencing: a survey. *International Journal of Production Research*, 41(16):3721–3759, 2003.

J.D. Linton, R. Klassen, and V. Jayamaran. Sustainable supply chains: An introduction. *Journal of Operations Management*, 25:1075–1082, 2007.

Y. Liu, K.L. Teo, and X.Q. Yang. Approximation methods for non-convex curves. *European Journal of Operational Research*, 117:125–135, 1999.

S. Matos and J. Hall. Intregrating sustainable development in the supply chain: the case of life cycle assessment in oil and gas and agricultural biotechnology. *Journal of Operations Management*, 25:1083–1102, 2007.

H. S. Matthews and D. H. Matthews. Information technology products and the environment. In R. Kuehr and E. Williams, editors, *Computers and the environment: Understanding and Managing their impacts*, volume 1, pages 19–39. 2005.

C. K. Mayers, C. M. France, and S. J. Cowell. Extended producer responsibility for waste electronics an example of printer recycling in the United Kingdom. *Journal of Industrial Ecology*, 9(3), 2005.

R. J. Orsato. Competitive environmental strategies: When does it pay to be green? *California Management Review*, 48(2):127–143, 2006.

M. E. Porter and C. Vanderlinde. Green and competitive - ending the stalemate. *Harvard Business Review*, 73(5):120–134, 1995.

P. Rao and D. Holt. Do green supply chains lead to competitiveness and economic performance? *International Journal of Production Economics*, 25(9):898–916, 2005.

B. Roy. Decision-aid and decision-making. *European Journal of Operation Research*, 45: 324–331, 1990.

S. Rubio, A. Chamorro, and F. J. Miranda. Characteristics of research on reverse logistics. *International Journal of Production Research (preview article)*, 2006.

I. Rudenauer, C.O. Gensch, and D. Quack. Eco-efficiency analysis of washing machines. Technical report, Oko-Institute e.V., 2005.

K. Ruediger. Managing pcs through policy: review and ways to extend lifespan. In R. Kuehr and E. Williams, editors, *Computers and the Environment: Understanding and Managing their impacts*, volume 1, pages 253–278. 2005.

M. Savage. Implementation of waste electric and electronic equipment directive in EU 25. Technical report, Technical report, European Commission, Joint Research Centre, 2005.

W. Scharnhorst. *Life Cycle Assessment of mobile networks with focus on the end-of-life products*. PhD thesis, Univesite de Lausanne, 2006.

W.S. Shin and A. Ravindran. Interactive multiple objective optimization: survey i- continuous case. *Computers & Operations Research*, 18(1):97–114, 1991.

T. Spengler, H. Puchert, T. Penkuhm, and O. Rentz. Environmental integrated production and recycling management. *European Journal of Operations Management*, 97:308–326, 1997.

R. Steuer. ADBASE Multiple Objective Linear Programming Package, Faculty of Management Science. University of Georgia, Athens, Georgia, 1988.

R. Teunter, Z.P. Bayindir, and W. Den Heuvel. Dynamic lot sizing with product returns and remanufacturing. *International Journal of Production Research*, 44(20):4377–4400, 2006.

M. Thierry, M. Salomon, J. Van Nunen, and L. Van Wassenhove. Strategic issues in product recovery management. *California Management Review*, 37(2):114–135, 1995.

A. Tukker, G. Huppes, J. Guine, R. Heijungs, A. Koning, L. van Oers, S. Suh, T. Geerken, M. van Holderbeke, B Jansen, and P. Nielsen. Environmental impact of products (eipro) - analysis of the cycle environmental impact related to the total final consumption of the eu25. full draft report, Institute for Prospective Technological Studies, 2005 2005.

N. Walley and B. Whitehead. Its not easy being green. *Harvard Business Review*, 72(3): 46–50, 1994.

G. Walther and T. Spengler. Impact of WEEE-directive on reverse logistics in Germany. *International Journal of Physical Distribution and Logistics Management*, 35:337–361, 2005.

K. A. Weitz, J. A. Todd, M. A. Curran, and M. J. Malkin. Streamlining life cycle assessment: consideration and a report on the state of practice. *The International Journal of Life Cycle Assessment*, 1(2):79–84, 1996.

E. Williams. Environmental impacts in the production of personal computers. In R. Kuehr and E. Williams, editors, *Computers and the environment: Understanding and managing their impacts*, volume 1, pages 41–72. Springler, 2005.

E. Williams and Y. Sasaki. Strategizing the end-of-life handling of personal computers: resell, upgrade, recycle. In R. Kuehr and E. Williams, editors, *Computers and the Environment: Understanding and Managing their impacts*, pages 183–195. Kluwer Academic Publishers, 2005.