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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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7 chains as those supply chains where is taken care of items once they are no longer desired or  
8 can no longer be used (Flapper et al. [2005]). Increased legislation in the field of producer  
9 responsibility, take-back obligations and setting up collection and recycling systems leads to  
10 a strong focus on CLSC management. In the European Union, legislation concerning the  
11 waste of electrical and electronic equipment (WEEE) has mandatory collection and recycling  
12 objectives since 2005 (see Savage [2005]). WEEE-alike legislation has also been introduced in  
13 Canada, Japan, China and a number of states in the US. Apart from environmental drivers  
14 (voluntarily or forced by legislation), it is sensible to believe that the economic agents within  
15 the supply chain aim at reaping the maximum benefit from the reverse part of the supply  
16 chain, as expected in any economic activity. The benefits are direct, i.e. profiting from re-  
17 selling, re-furbished equipments, spare parts or virgin material (Fleischmann et al. [2000]).  
18 Returned products often contain value to be recovered in one way or another.  
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27 Sustainable supply chains are not clearly defined yet. A popular definition states that sus-  
28 tainable supply chains require coordination of social, environmental and economic dimensions  
29 (the triple bottom line), see e.g. Matos and Hall [2007]. Closing supply chains is regarded  
30 as environmentally friendly, in casu sustainable. Taking care of end-of-use items instead  
31 of disposing them, is assumed to be a proven measure to improve sustainability of supply  
32 chains (Geyer and Jackson [2004]). A major assumption underlying take-back legislation is  
33 again that recycling and recovering larger quantities of materials will lead to a reduction of  
34 environmental impacts.  
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41 Literature from the last decade provides quite some examples of good alignment between  
42 business and the environment in supply chains (e.g. Rao and Holt [2005]). In these examples  
43 closing the loop yields environmental gains even if business economics is the main driver  
44 (Guide and Van Wassenhove [2003], Guide et al. [2003]). Situations where business and the  
45 environment objectives are perfectly aligned are called “win-win”, “double-dividend”, “free-  
46 lunch” (Orsato [2006]), or “low hanging fruit” situations. On the other hand, studies are  
47 known where trade-offs do occur between what is economically rational in the supply chain  
48 and what is sustainable for the population as a whole (e.g. Walley and Whitehead [1994]).  
49 Integrating sustainability in supply chain models does increase the complexity of the models  
50 a lot (Matos and Hall [2007]). This seems more urgent in a trade-off situation than in a  
51 win-win situation. Therefore, an interesting question is: can we differentiate between the  
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7 win-win situations and the trade-off situations in this field? In this paper we will analyze if  
8 and for which cases the assumption of a sustainable closed-loop supply chain does hold. We  
9 will discuss circumstances where the assumption is not fulfilled.

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

## 2 The sustainable (closed-loop) supply chain concept

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46 Sustainability is not yet operationalized in Operations Management literature. The most  
47 used definition is “using resources to meet the needs of the present without compromising the  
48 ability of future generations to meet their own needs” (WCED [1987]). This definition is rather  
49 abstract and raises more questions than answers. Linton et al. [2007] transfer the concept of  
50 sustainability to supply chains and state that: A sustainable supply chain is a supply chain  
51 integrating issues and flows that extend beyond the core of supply chain management such  
52 as product design, manufacturing by-products, product management during use, product life  
53 extension and recovery processes at end-of-life. Figure 1 represents a general framework for  
54 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

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7 systems are reviewed in Thierry et al. [1995] and Gungor and Gupta [1999]. An important  
8 decision problem in this category of models is which parts to disassemble for reuse opportu-  
9 nities. This question has long been studied in the mainstream of CLSC, see Lambert [2003].  
10 Deterministic and stochastic models where parts out of disassembled products are re-used for  
11 production of new products are described by a.o. Guide et al. [2000], Bayindir et al. [2003]  
12 and Inderfurth [2004].

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

### 3.3 Supply chain model issues in reverse logistics

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

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59 These types of recent models look very promising for including sustainable issues. The  
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7 presented models are normally applied to complex products, e.g. electrical products (an  
8 exception are the distribution and recycling models that are also applied to materials like  
9 sand or carpets). Therefore, we analyze the environmental impact of such complex products  
10 exemplarily within the next section.  
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#### 13 14 15 **4 Environmental impacts of electrical and electronic equip-** 16 17 18 **ment** 19

20 Awareness of the environmental impact of products is a recent trend. This trend has fostered  
21 a number of analyses on the environmental impacts of consumption in European households.  
22 Supermarkets label their products with environmental foodmiles, firms invest in communi-  
23 cating the environmental impacts of their products (e.g. “Greening your Apple”), etc.  
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26 The Electronic and electrical product category appears as a large source of environmental  
27 footprint (Tukker et al. [2005]). The production and usage of washing machines, refrigerators  
28 and freezers, telecommunication devices, audio and video equipments are responsible for ap-  
29 proximately 8% of the overall generated global warming potential in a household. Labouze  
30 et al. [2003] show that electric equipments are responsible for 10% to 20% of the overall en-  
31 vironmental impact on the categories depletion of non-renewable sources, greenhouse effect,  
32 air acidification, years of lost life, and dust.  
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35 Closing the supply chain is advocated to mitigate the environmental impact of the electric  
36 equipments our society consumes. Studies like Labouze et al. [2003] and Mayers et al. [2005]  
37 calculate the environmental impact of a product using a list of various environmental impact  
38 indicators, such as human toxicity, ecotoxicity, photochemical oxidation, acidification, ozone  
39 layer depletion etc. Mayers et al. [2005] conclude in their study that the targets of the WEEE  
40 legislation could easily lead to mixed results from a life cycle perspective. Some environmental  
41 impacts decrease while others increase. Furthermore, WEEE legislation targets have no  
42 incentive to adapt the design of products, improving the environmental impacts in an earlier  
43 stage of the life cycle.  
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46 We analyze the magnitude of the environmental impact using a single measure of environ-  
47 mental impact: Cumulative Energy Demand. This measure aggregates other environmental  
48 indicators in terms of energy demand. Recent studies show a high correlation between this in-  
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icator 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

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7 extreme case consume up to 8% of the energy needed over the entire life cycle of the product.  
8 The CED distribution for the production, including assembling, transportation, and usage  
9 phase in a no loop supply chain is represented in Figure 2.

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

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

#### 41 **4.2 Refrigerators, washing machines, and TV sets**

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

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7 more energy consuming than new ones. Based on the examples in Section 4, it seems to  
8 make more sense to refurbish computers than to refurbish TV sets. For products like TV sets  
9 and washing machines, it seems to be crucial to save energy during the lifetime (see column  
10 “manufacturing” in Table 1). However, as soon as products are sold, the manufacturer can  
11 no longer influence energy demand. Therefore, measures already have to be taken during the  
12 design phase of the product. Thus, the influence of reverse logistics is limited for these prod-  
13 ucts. As soon as new energy-saving equipment is on the market, remanufacturing strategies  
14 might even contradict sustainable aspects.  
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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

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7 higher costs, e.g. higher costs in production, but might then result in lower costs during  
8 remanufacturing. The same holds for LCA results. Thus, profitability and environmental  
9 advantageousness of such measures becomes only clear if the whole life cycle is taken into  
10 account. The prerequisite for design for remanufacturing/design for recycling measures is  
11 an adequate anticipation of future remanufacturing and recycling processes. This can be  
12 done applying disassembly models ex-ante. Doing so, problematic materials for recycling,  
13 challenging connections, or harmful substances can be detected.  
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### 20 **5.2.3 Realize the reverse logistic measures that are economically and ecologically** 21 **feasible**

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24 In later life cycle phases of the product, realize only reverse logistic measures that are eco-  
25 nomically and ecologically viable. For some products, it might not be sensible to extend the  
26 lifetime, while at the end of the useful life of a product it is always important to focus on  
27 harmful and scarce substance.  
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31 (a) Apply classical reverse logistics models if economic and ecological results are align. If  
32 applied to the right products and the right life cycle phases, the models described within  
33 section 3.1 and 3.2 can be integrated in this step. The application of distribution and recycling  
34 models is mainly needed during the recycling stage as shown in the column “recycling” in table  
35 1. As long as only transportation processes are to be optimized, straightforward economic  
36 driven distribution models will be sufficient in almost all cases. For example, routing models  
37 aim at the reduction in transportation kilometers (business objective), which is in turn directly  
38 correlated to reductions in the fuel consumption (environmental objective). However, as soon  
39 as the focus is on scarce and harmful substances, economic objectives are not sufficient any  
40 more. In recycling, it can be important to remove harmful substances even though it is  
41 not economically feasible to do so. The trade-offs between environment and profit might even  
42 increase if distribution and recycling is looked at with integrated models. It might be the case  
43 that transportation increases because of higher recycling, since recycling facilities are often  
44 further away than land-filling sites (Walther and Spengler [2005]). With regard to these results  
45 an extension of disassembly models, which can easily be transferred to integrated distribution  
46 and disassembly models, is presented in paragraph b). For products with high impact in  
47 the production stage (column “production”), integrated production planning and inventory  
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7 management models are important in order to apply remanufacturing strategies. As shown in  
8 section 3.2, measures like refurbishing, remanufacturing or reuse are often economically viable.  
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10 Purely economic models seem to be sufficient - but only if applied to the right products (see  
11 section 4). However, in order to answer the question which components to reuse, trade-offs  
12 might occur. The consequence of purely economic criteria can be that components with  
13 high environmental and low economic yield will not be recovered and likely end up in bulk  
14 recycling with little or no environmental reclamation. Therefore, the disassembly models in  
15 the integrated production planning and inventory management models should be extended  
16 with regard to environmental criteria. We will show such an extension in section 6.  
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22 (b) Extend the classical models if there is a trade-off between environment and profit.  
23 Based on the examples studied, the risk of losing environmental gain by one-dimensional  
24 economic optimization is substantial as soon as trade-offs between ecological and economic  
25 issues occur. Therefore, some models have to be extended to multiple objective models. As  
26 shown above, disassembly planning is a core approach when aiming at sustainable supply  
27 chains for complex products. First, ex-ante optimization of disassembly is already helpful for  
28 improvements within the design stage of a product. Second, disassembly models are necessary  
29 in order to determine the components to be remanufactured and reused when extending the  
30 lifespan of a product. Doing so, functionality of products and parts can be recovered, and thus  
31 environmental impacts like resource depletion and greenhouse gas emission can be reduced.  
32 Third, it is also necessary to determine optimal disassembly depth and material fractions to  
33 be generated during the recycling stage aiming at the removal of harmful substances and  
34 gaining of scarce materials at the end of the useful life of a product. However, when looking  
35 at disassembly models, the optimal economic disassembly decision is not necessarily the best  
36 solution for the environment: components with high potential environmental gains and low  
37 profit margin are left in the original equipment to be recycled or directed to landfill. Therefore,  
38 these models are to be extended with regard to environmental objectives.  
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## 6 Application of the framework: Eco-efficient lotsize with re-manufacturing 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

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

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

$$x_t, y_t, z_t, u_t, v_t \geq 0 \quad \forall t = 1, \dots, T$$

## 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 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

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7 determine what precisely is the solution sought. In broad terms, solving a multi-objective  
8 problem involves the following steps (i) identifying the solutions that are not dominated, (ii)  
9 capturing the decision maker preference, or eliciting preference and (iii) aiding on the decision  
10 regarding the “best” or preferred solution.  
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13 For item (i), the endeavor is purely mathematical, and for this particular problem, trivial.  
14  $\epsilon$ -constraint methods, weighted sum optimization and lexicographic optimization are examples  
15 of formulations that will yield Pareto optimal solutions in polynomial time. Fulfilling the goals  
16 presented in items (ii) and (iii) is less trivial (Roy [1990]). In fact, as the large number of  
17 different methodologies proposed to elicit such preferences suggest, the task is very complex.  
18 In a nutshell, these methodologies are divided in three types (Evans [1984]). The classification  
19 regards the timing in which the preference is elicited. The first type of methods are those  
20 requiring a prior articulation of the preferences. The preferences may be expressed by weights  
21 concerning the relative importance of each objective function, minimum thresholds for the  
22 value of the objective functions, or nadir points, to name some. Examples of such formulations  
23 are the  $\epsilon$ -constraint methods, weighted sum scalarization, and lexicographic optimization. For  
24 a description of these models see Chankong and Haimes [1983].  
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34 The second part consists of the so called interactive method, e.g. ELECTRE (Roy [1968]),  
35 STEM (Benayoun et al. [1971]), Pareto Race (Korhonen and Wallenius [1988]), and UTA  
36 (Jacquet-Lagrange and Siskos [1982]). In these methods the user interacts with the formula-  
37 tions. The basics steps of the interactive methods are two, which are sequentially repeated  
38 until the desired solution is reached. The steps are (i) find a (preferably) feasible solution,  
39 and (ii) interact with the DM and get a reaction from this solution (Shin and Ravindran  
40 [1991]). The algorithm stops whenever the decision maker is satisfied with the solution.  
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46 The third type of formulations advocates the characterization of the efficient frontier. The  
47 frontier can be characterized by the enumeration of its efficient vertices for Multi-objective  
48 Programming (MOLP). For this purpose, one of the most common methodologies is the multi-  
49 objective simplex method. For the bi-objective case, another way to characterize the efficient  
50 frontier is to approximate it (Fruhirth et al. [1989], Liu et al. [1999], and Fernandez and  
51 Toth [2007]). The visual representation of the approximated frontier improves the decision  
52 process (Fernandez and Toth [2007]).  
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## 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:  $P_t = 200$ ,  $H_t = 60$ ,  $R_t = 150$ ,  $W_t = 50$ ,  $S_t=20$ ,  $\forall t = 1, \dots, T$ . 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:

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

$$E_x=5000, E_z=500 \text{ and}$$

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

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

(insert figure 5)

The inventory for each of the extreme efficient points presented in 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

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7 to a preferable eco-efficient solution. Figure 5 and 6 show that the extreme efficient solution  
8 H (minimize costs) really differs with the extreme efficient solution A (minimize CED), both  
9 in objective values as in inventory patterns. This confirms our statement that the classical  
10 models should be extended if there is a trade-off between environment and profit.

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

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

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## 7 Conclusions

Some ten years ago we witnessed a hot discussion between those advocating environmen-  
tal 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? Is 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.

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figures and tables

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

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

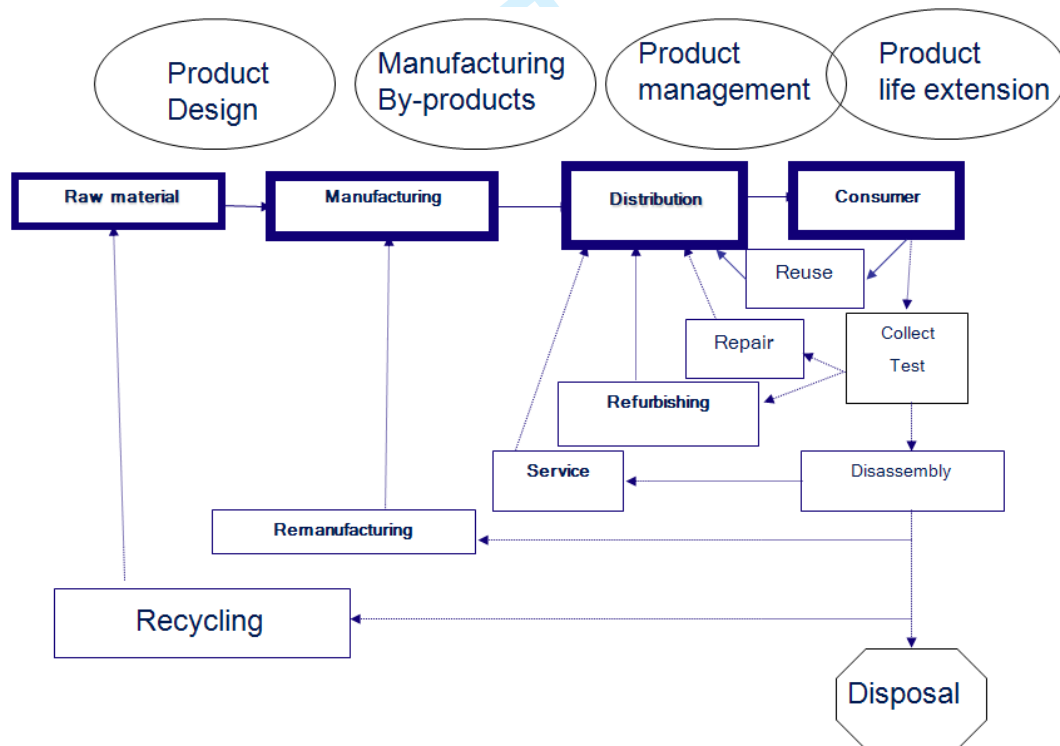


Figure 1: General frame for a closed-loop (sustainable) supply chain

## Energy use in the product lifecycle

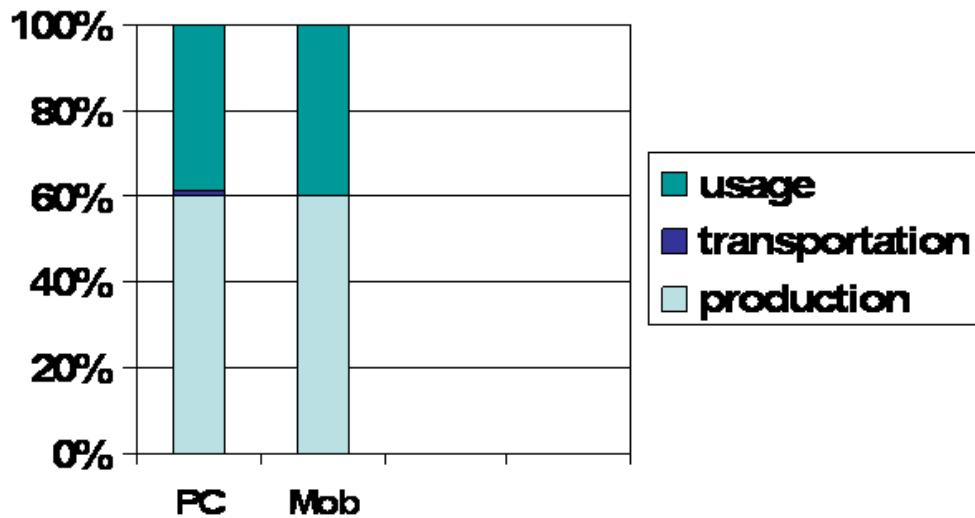


Figure 2: Energy consumption profile for PCs and mobiles

## Energy use in the product lifecycle

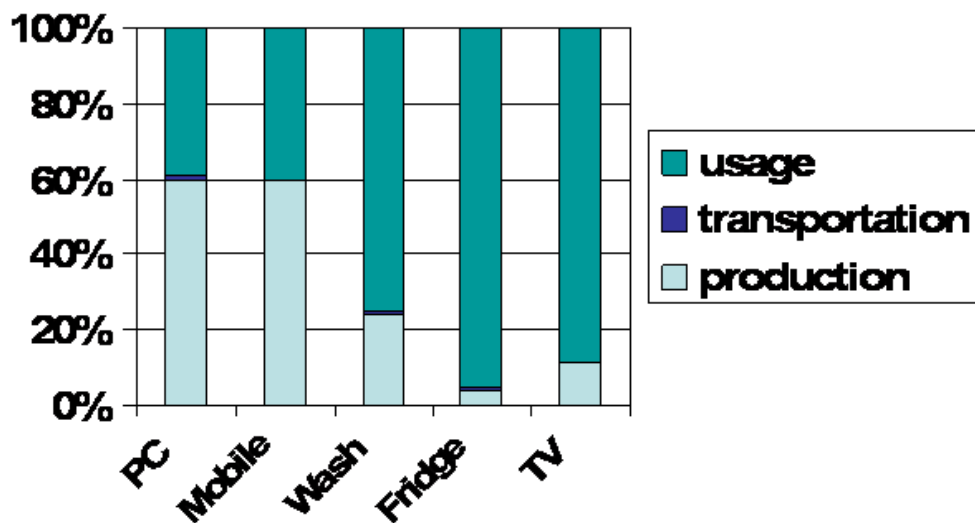


Figure 3: Energy consumption profile for PCs, mobiles, washing machines, fridges and TVs



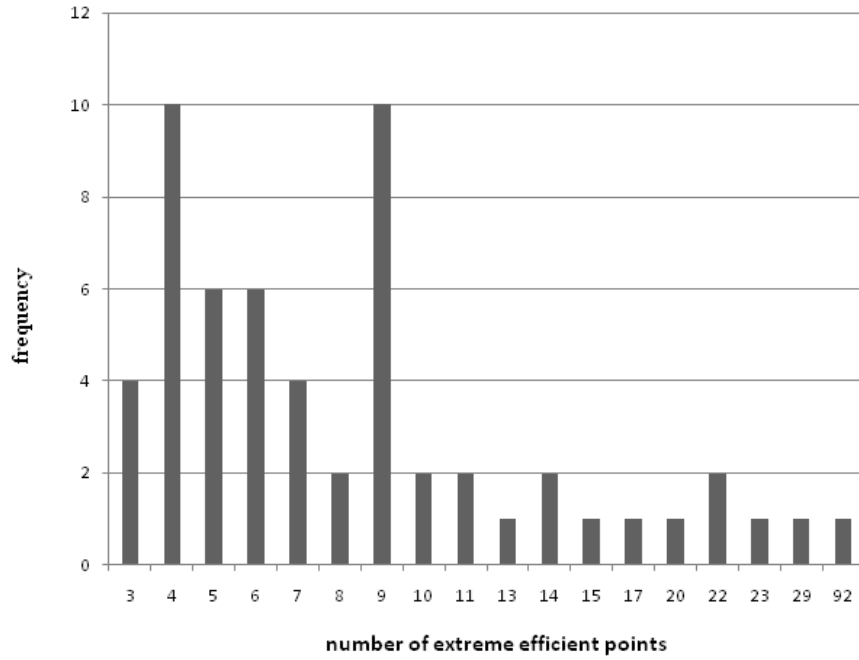


Figure 4: Number of extreme efficient points

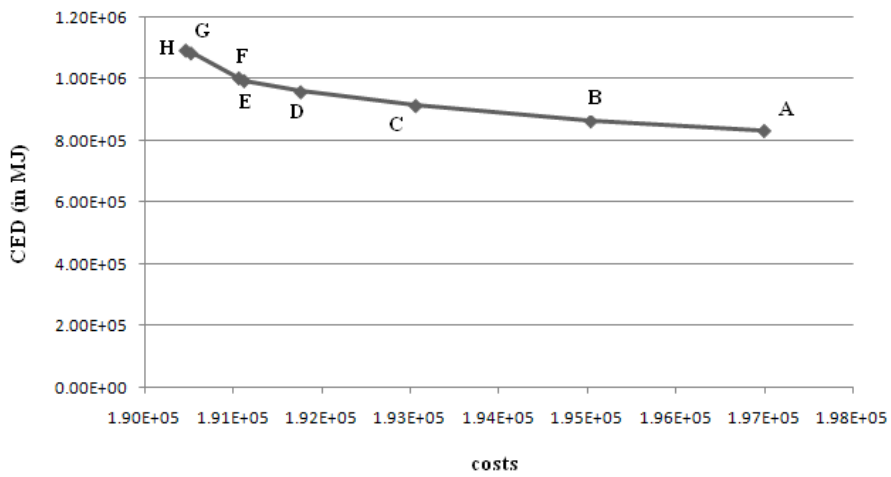


Figure 5: Pareto optimal frontier

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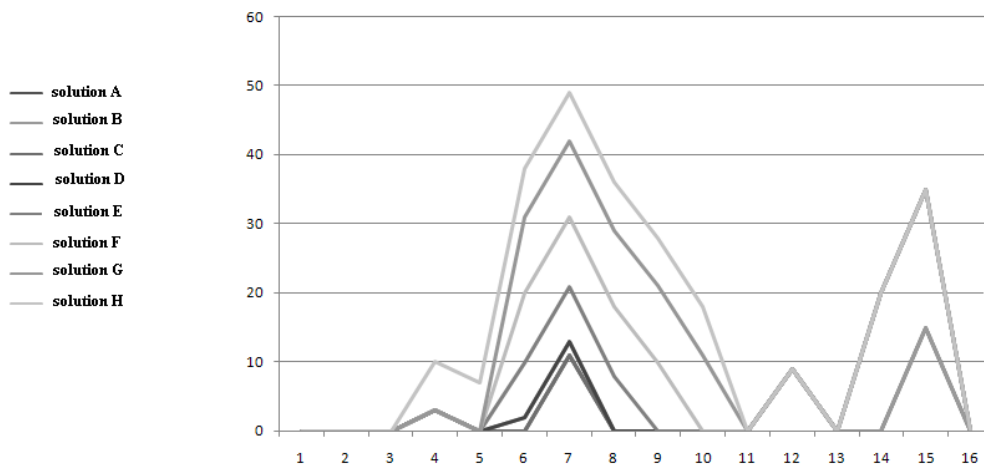


Figure 6: Inventories for the different solutions

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