From Closed-Loop to Sustainable Supply Chains: The WEEE case

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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 reap the maximum economic benefit from end-of-use products. Nevertheless, literature within this stream of research advocates that closing the loop helps to mitigate the undesirable footprint of supply chains. In this paper we assess the magnitude of such environmental gains for Electric and Electronic Equipments (EEE), based on a single environmental metric of Cumulative Energy Demand. We detail our analysis for the different phases of the CLSC, i.e. manufacturing, usage, transportation and end-of-life activities. According to our literature review, within the same group of EEE, results greatly vary. Furthermore, based on the environmental hot-spots, we propose extensions of the existing CLSC models to incorporate the CED.

1 Introduction

The migration from open-loop to closed-loop supply chains has been long regarded as environmentally friendly. Literature is littered with examples of good alignment between business and the environment in supply chains. Nevertheless, it is sensible to believe that the economic

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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 (Thierry et al. [1995], Fleischmann et al. [2000]) or indirect, i.e. promoting a green image, meeting customers demand or preparing for further legislation (Fleischmann et al. [2000], Fleischmann et al. [2001], de Brito [2004], Toffel [2004]).

Despite the fact that closed-loop supply chains are driven by self-interest of the agents involved (Guide and Van Wassenhove [2003], Guide et al. [2003]), literature on the field advocates that closing the loop also unintended yields some environmental gains. Those situations where business and the environment objectives are perfectly aligned are called "win-win", "double-dividend", "free-lunch" (Orsato [2006]), "low hanging fruit" situations (Geyer and Jackson [2004]). In the second section of this paper we particularly focus on these "win-win" situations in CLSC (considering direct and quantified economic returns only): i.e. reselling refurbished equipment, components as spare parts, or reclaimed virgin materials. In figure 1, therefore, we are interested in the solutions belonging to the upper-right quadrant.

(insert figure 1)

In more detail, we intend to estimate the environmental burn reduction regarding the following improvement or implementation of the following activities in a supply chain: reduction in the transportation on the reverse channels of the supply chain, implementation of refurbishing, remanufacturing or re-use, spare parts reclaiming and recycling. In order to make those estimates meaningful we compare them with the total environmental burn of the complete life cycle of the product. We analyze five items covered by the European Directive on Waste of Electrical and Electronic Equipment (WEEE), namely a TV set, a personal laptop, an refrigerator, an mobile phone and an washing machine.

In the third section of this paper we extend our analysis to the "win-lose", "lose-win" quadrants and, based on the environmental hot-spots defined in the second section, extend the classical operations research models in CLSC into models incorporating the environmental impact of the supply chain.

The paper is therefore organized as follows: the second chapter present the main activities influencing environmental burn for closed-loop supply chains, namely: raw material extraction, transportation, manufacturing, usage, and end-of-life. Furthermore, we estimate the environmental impact for each of these activities for the EEE in analysis. The third chapter presents a brief literature review of the existing CLSC models and a framework for extending such models to incorporate environmental impact (whenever sensible to do so), as well as an estimative for the environmental gains in "win-win" situations, i.e. given that reduction in transportation positively impacts both environment and business, how much transportation can we reduce by properly allocating the disassembling facilities? Last chapter brings the conclusion and the answer for our research questions: Do closed-loop supply chains significantly outperform no loop ones when economic driver is the only motivation? Do the improvements or implementation of different phases of closed-loop supply chains matter for the environment? Are these findings generalizable or product dependent? How to extend the existing O.R. models applyed in CLSC to integrate environmental impacts?

2 What environmental impacts have the different phases of my reverse chain?

Europe is currently on the transition from an product's end-of-use oriented to a integrated product oriented policy. The recent trend has fostered a number of analysis on the environmental impacts of the total final consumption in European households. After transportation and food consumption, the EEE category appears as the third biggest source of environmental footprint (Tukker et al. [2005]). The production and usage of washing machines, refrigerators and freezers, telecommunication devices, audio and video equipments, for instance, are responsible for approximately 8% of the overall generated global warming potential in a household. For Ozone layer depletion, human toxicity, ecotoxicity, photochemical oxidation, acidification and eutrophication, the environmental impact caused by EEEs is, respectively: 5%, 6%, 6%, 5%,11% and 1%. Labouze et al. [2003] shows that EEEs are responsible for $10\% - 20\%$ 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 EEEs our society consumes. In the next subsections we analyze the magnitude of such reductions using a single measure of environmental impact: Cumulative Energy Demand. Recent studies show a high correlation between this indicator and the Eco-indicator 99 aggregated result. The result is also quite robust for the disaggregated environmental impact indicators, i.e. resource depletion, marine toxicity, etc. (Helias and Haes [2006]). Walk et al. [2005] finds an overall Spearman correlation of $\rho^2 = 0.94$ between the CED and the aggregated Eco-indicator results, as well as individual impact correlations ranging from $\rho^2 = 0.73$ to $\rho^2 = 0.96$. Follows the environmental impact estimations for a personal computer, a mobile phone, a refrigerator, a tv and a washing machine. The results are based on secondary data from other studies, as well as existing environmental impact databases.

2.1 Environmental impact of a personal computer and a mobile

Computers have become common appliances in households of developing nations. The volume of personal computers sold in the world has grown from thousands, in the beginning of the eighties, to more than a hundred million units in 2002 (Matthews and Matthews [2005]). Furthermore, life cycle span has drastically diminished during the last twenty years, causing large amounts of computer waste all over the world. Besides the "traditional" environmental pressure categories, i.e. acidification, eutrophication, etc, 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 (from Niger, to China or India) instead of providing a proper end-of-life treatment for such products. Greenpeace has denounced such abuses and lunched the campaign "Hi-Tech: Highly toxic" (Greenpeace [2006]). In this section we analyze the Cumulative Energy Demand only, so the toxic substances founded in a personal computer are not included in the analysis.

Comprehensive results on environmental impact of computers are scarce. We base our analysis on the results obtained by Williams [2005]. For a PC, a total of 240kg of fossil fuel is used to produce a computer. Contrary to most of the other electric and electronic appliances, the highest environmental burn is due the production phase. The usage phase is responsible for 25% of the computers environmental burn (Williams [2005]). As a comparison, Williams [2005] provide the following data: an automobile requires 2000kg of fossil fuel to be produced, so the fossil fuel demand of a personal computer life-cycle per year is approximately 60% of a car's fuel demand for production.

Another interesting result for computers: although the production phase yields most of the environmental footprint, reclaiming such burns via traditional bulk recycling is impossible.

The reason for such apparent paradox lies on 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. The CED distribution for the production, including assembling, transportation, and usage in a no loop supply chain is represented in figure 2 [1]:

(insert figure 2)

Note that the transportation phase's environmental impact is irrelevant if compared to the complete life cyle's environmental impact. It is worth to mention, however, that transportation's impact may vary from irrelevant to small, depending on the assumptions made. For desktop computers, Williams and Sasaki [2005] suggests that transportation cannot be discarded regarding energy consumption: in a worst-case scenario of $5.000km$ traveled by an $24k$g computer, by truck, the energy consumed by transportation is estimated in $680MJ$, around 10 percent of the energy necessary to produce the computer, and approximately 8% the energy consumed in the entire life cycle of the product. As Williams and Sasaki [2005] points himself, the difference between the worst to the best case scenario for transportation's environmental impact might be tenfold.

The aforementioned results align with those found by Gotthardt et al. [2005]: In a desktop the production phase is responsible for 60% of all the energy consumed, meanwhile usage consumes 39% and transportation around 1%. Figure 3 illustrates our findings.

(insert figure 3)

A sensible way to improve the life cycle of a computer is, therefore, to extend its life-cycle. Doubling from two to four year its life cycle would render a reduction of approximately 31% on the overall environmental impact. Re-selling, repairing, re-furbishing and re-manufacturing seem the best alternatives to claim environmental value for personal computers and closing the loop with such activities might indeed help to mitigate such environmental impacts. These results align with those found in Ruediger [2005].

The results for mobile phone resemble those for computers. Gotthardt et al. [2005] results show that the environmental impact contribution of bulk recycling phase is irrelevant. Furthermore, production phase is responsible for approximately 60% of the overall environmental

[1] for detail on data, assumptions and calculations, see annexes

impact, excluding transportation. In that case, however, transportation does not significantly contribute to the overall environmental impact. The environmental impact distribution of a mobile is presented in figure 4

(insert figure 4)

The reason for manufacturing to dominate the energy consumption in mobiles seems to lie, as in computers, in their embedded electronic pieces, such as printed circuit boards for mobiles (Scharnhorst [2006]) and semiconductors, printed circuit boards and semiconductors in computers (Williams [2003]). For electronic equipment, therefore, little energy can be claimed via bulk recycling, but a substantial amount can be reclaimed via re-using of components and equipments and re-furbishing or re-manufacturing of old electronic equipment. Furthermore, extending the life time for computers and mobiles will also diminish the pressure over raw material.

2.2 Environmental impact of a a refrigerator, washing machine, and a tv set

The use of household refrigerators and freezers is one of the main sources of environmental impact for EEE. In refrigerators, however, usage is the activity that, by far, demands most energy (Williams [2005]). For a refrigerators, $1,330kg$ of fossil fuel are consumed to produce and use an refrigerator, and 96% is consumed during the usage phase. For refrigerators, the CED distribution for production, transportation and usage is presented in figure 5.

(insert figure 5)

For a washing machine the results for CED are also aligned with those found for a refrigerator. The energy required for the usage phase is approximately 3/4 of the overall required energy required for the whole Life Cycle (Rudenauer et al. [2005]).

Watching TV is also a considerable source of environmental impact within the EEE group. The energy consumption profile of a tv is close to the refrigerator. The usage phase, for the tv, is responsible for 89% of the overall CED (Behrendt et al. [1997]). The impact of recovery for tvs also seems quite limited. For tvs, the CED distribution for production, transportation and usage is represented in figure 6.

(insert figure 6)

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

3 How to expand classic O.R. models (in CLSC) to mitigate environmental and costs impacts for the different phases of my reverse chain?

Operations Research is regarded as a powerful tool for decision making in supply chains. A wide variety of models have been proposed to deal with the different phases of a supply chain: vehicle routing, location-allocation of facilities, inventory management, etc. In some of these models, business and the environment objectives are perfectly aligned, i.e. routing models aim the reduction in transportation (business objective), which is by turn directly correlated to reduction in the fuel consumption (environment's objective). In others there is a trade-off between business and the environment. The disassembling for re-use of spare parts is accepted as environmentally friendly. The optimal economic disassembling decision is, however, not necessarily the best solution for the environment: components with high potential environmental impact's recovery and low profit margin are left in the original equipment to be recycled or directed to landfill. Figure 7 presents these main activities.

(insert figure 7)

3.1 reducing transportation via VRP (Vehicle Routing Problem) techniques

In order to give an estimate on the reduction of fossil fuel emission due routing we posit a reduction between 5% – 20% in transportation due better routing. We also analyze that a unitary percentage reduction on transportation has on the total cumulative energy demand of the electronic equipment.

For TV-sets, for instance, Behrendt et al. [1998] advocates that the energy consumption during transportation is irrelevant: it is assumed an 95MJ energy consumption at this phase. Using the aforementioned quite pessimistic estimation of Williams and Sasaki [2005] and comparing with the estimation of global consumption of a set set, this value is still not very significant: it represents only 2.5% of the total consumption. Similar results for the other EEE indicate that reduction in transportation for electric and electronic products is insignificant. The assumption that distribution, and possible improvements in distributions have little or insignificant effect on the total energy consumption seems quite robust for all the products. Note, however that we do not consider the transportation for suppliers and their subsequent suppliers. The first reason is practical: it is very hard to estimate the transportation for all the actors of the supply chain. Second, modeling of allocation is usually applied to the last phase of the supply chain: from OEM to warehouses to consumers, or OEM to consumers. Third, including the environmental impact of transportation from the suppliers to the OEM as a constant, will only decrease the comparative impact of distribution on energy consumption for the entire life cycle.

3.2 Re-manufacturing, re-use, re-furbish: disassembling selection

For electronic products, namely, computers and mobiles, the production phase responds to the higher proportion of energy consumed. For these products, extension of life-time usage and environmentally friendly end-of-use destinations will both reduce energy consumption and waste disposal per unit of time. Among the aforementioned "category" of products, some are also particularly unsensible to material recovery regarding energy and virgin material gains. Electronic equipment, including personal computer and mobiles, are examples. For desk top computers, the production phase is responsible for, approximately, 75% of the overall energy consumed (Williams [2003]). Furthermore, the proportion of virgin material and energy that can be reclaimed for such equipments is very small. The most attractive alternative for reducing environmental impact for such equipment is, therefore, increasing their lifespan (Kuehr [2003]). Repairing, Refurbishing an Remanufacturing computers seems, therefore, win strategies for the environment at its many dimensions. They reduces the amount of end-of-use equipments, thus reducing eco-toxicity and human toxicity, as well as energy consumption by simple expanding the lifespan of products.

Refurbishing can also decrease environmental footprint on electric and electronic equipment by adding some years on the usage phase of the equipment. This phase of the supply chain is not, however, entirely environmentally friendly: aging equipment are prone to be more energy hungry than new ones. Laundry machines, refrigerators, tv and other house appliances consumes much more energy during their lifetime that during their production phase. The statement is, however, limited to equipment's energy demand. On the other hand, refurbishing helps to slow down the pace for virgin materials and in the case where WEEE legislation do not exists, or is not properly enforced, the velocity in which these virgin materials and the respective toxic components, i.e anti-inflammable for computers or lead in TV sets and computer monitors, are paced down.Figure 8 show illustrate those findings.

(insert figure 8)

4 Extending the disassembling decision models - An eco-efficient approach

As presented in sections two and three, remanufacturing, refurbishing, spare part reclaiming and re-using may significantly mitigate environmental impact in the supply chains of computers and mobile phones. The decision problem of which parts to disassemble has been long studied in the mainstream of CLSC (for an overview on disassembly see Lambert [2003]), but environmental impacts are not included in such formulations. The existing research mainstream focus on the economic return of the activity, and posit that the remanufacturing yields environmental benefits. The focus is therefore, on the "win-win" disassembling configurations for business and the environment. Components with high environmental and low economic yield ,for example, are less prone to be removed, and more likely to end up in bulk recycling with little or no environmental reclamation.

In this section, based on the significant negative environmental impact of extending the life cycle of units and spare parts for computers, we propose the extension of the traditional disassembly formulation to include environmental parameters. We extend the Lambert [2003] formulation, including the two aforementioned functions: CED and waste.

$$min \;\; z_1 = \sum_i \sum_j (-T_{ij} r_i + c_j) x_j \tag{1}$$

$$min \;\; z_2 = \sum_i \sum_j (-T_{ij} e_i) x_j \tag{2}$$

$$min \;\; z_3 = \sum_i \sum_j (-T_{ij} w_i) x_j \tag{3}$$

subject to node equations:

$$\sum_j -T_{ij} x_j < 0 \qquad x_{j=1} = 1 \tag{4}$$

where T_{ij} is the transition matrix, x_j are flow variables, r_i are subassembly revenues, w_i are waste reductions,e_i are energy gains, and c_i are action costs. The model differ from (Lambert [1999]) by equations 2 and 3. We extend such models to incorporate the environmental variables. The extension of such models has been indicated as further research, and the results in the previous sections show that it is sounded to do so for mobiles and computers. It is worth to mention that such models extensions, from closed-loop to sustainable supply chains should be always preceded by a life cycle analysis of the entire life of the product, as we pointed out in the previous section.

The extension of models from single to multi-objective, meaning the switch from an optimal search to an (strong) Pareto efficient solution, is well documented in literature. In the case of disassembling, the CPU-time for solving the problem to optimality is usually insignificant, despite the NP-hardness of the problem (Lambert [2003]).Once the number of disassembling combinations is, for most of the problems, small (Lambert [2003]) one solution is to simply enumerate all possible solutions. The algorithm for finding all supported or supported and supported solutions is the following:

procedure eco-frontier (**var:** ND:LIST);

enumerate all possible solutions

for finding the supported efficient solutions solve, for every problem the following LP † [2]

Min Θ

st

$\Theta f_i(\hat{x}) - \lambda_i f_i(x) \geq 0, \qquad i = 1, .., 3$

Θ free and $\lambda_i \geq 0, \qquad i = 1, .., 3$

for finding the supported and unsupported solutions, compare each solution pairwise with the others. if there is no solution x such that $f_i(x) > f_i(\hat{x})$ for at least one i and $f_i(x) \geq f_i(\hat{x})$ for all i, then the solution is Pareto Efficient.

A second way to find supported Pareto Optimal solutions for the problem is via the weight-sum scalarization of the objective function (1),(2),(3), subjected to (4).A fourth way to find supported and unsupported solutions is to reduce the problem to TSP (see Lambert [1997]) and then solve as proposed by Ehrgott [2000]. Numerical analysis is still required to determine the less CPU-consuming way for such calculations

5 conclusions

In the nineteenths we witnessed a hot discussion between those advocating environmental improvement as a driver of competitive advantage (Porter and Vanderlinde [1995],Gore [1991]) 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. In this paper we search for "win-win" situations due the adoption of traditional CLSC models, and we show one example of how to extend a CLSC formulation towards a sustainable one. Both aforementioned approaches are applied to Electric and Electronic Equipment.

For EEE, transportation do not appear to be significant for the overall environmental impact, despite its appealing "win-win" nature. Adoption of re-use, re-manufacturing and refurbishing activities appears to positively impact environmental quality for computers and

[2]† The formulation is nothing but the standard DEA model applied to the image of the combinations of disassemblies

mobiles, which is not clear for the analyzed electric equipment. For computers and mobiles, therefore, the models for disassembling decisions are particularly suitable to be extended from CLSC only, to Sustainable Supply Chains. We present a simple algorithm to calculate all supported and unsupported solutions for such problem. The expected CPU time is small, considering the results of Lambert [2003].

5.1 Figures

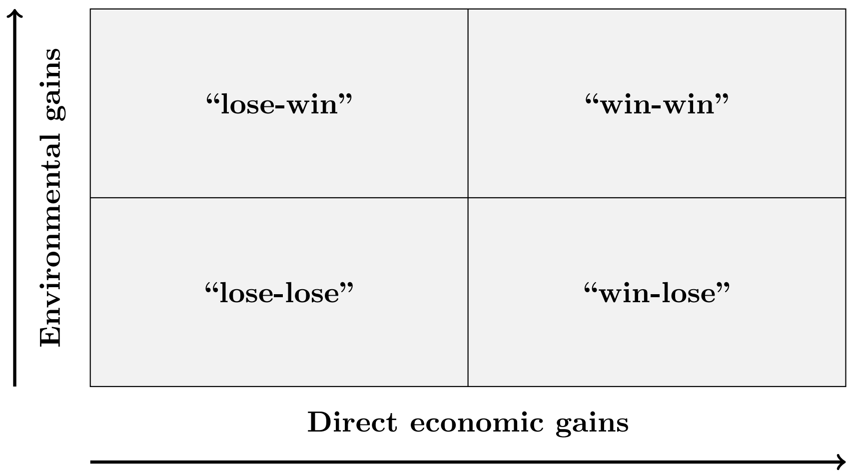

Figure 1: Relationship between business and the environment in supply chains. Adapted from Geyer and Jackson [2004]

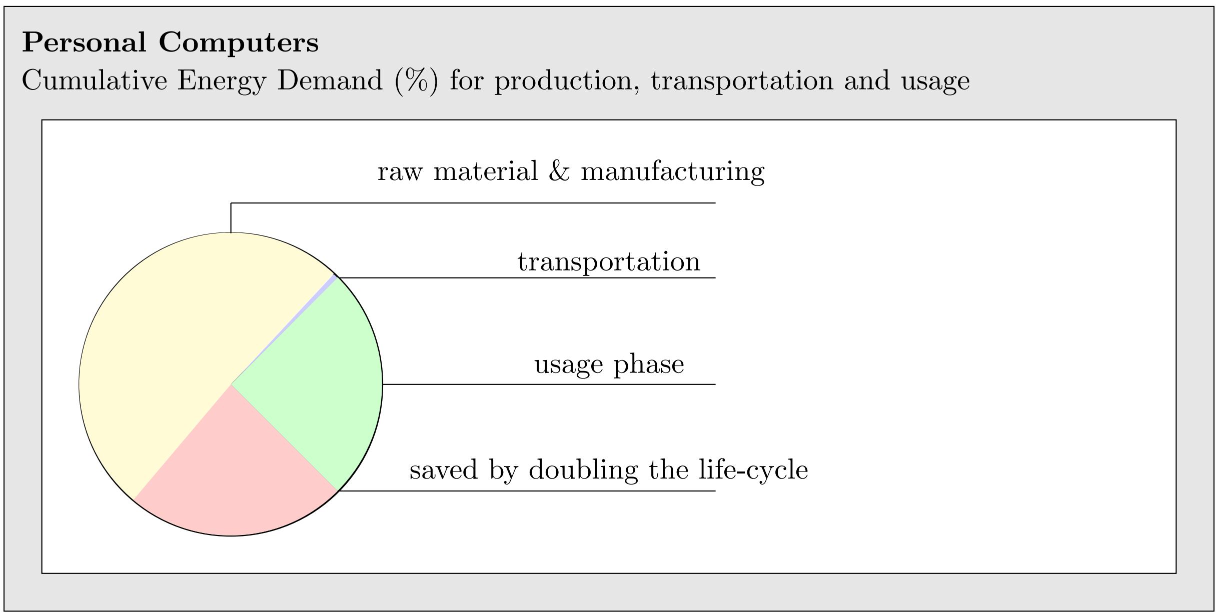

Figure 2: Cumulative Energy Demand (%) for the different phases of the life cycle of a personal computer. Data for production and usage obtained in Williams [2005]. Transportation's environmental impact is estimated using BUWAL-250 data for transportation consumption. It is assumed a transport moment of $10.000 kg \cdot kg$.

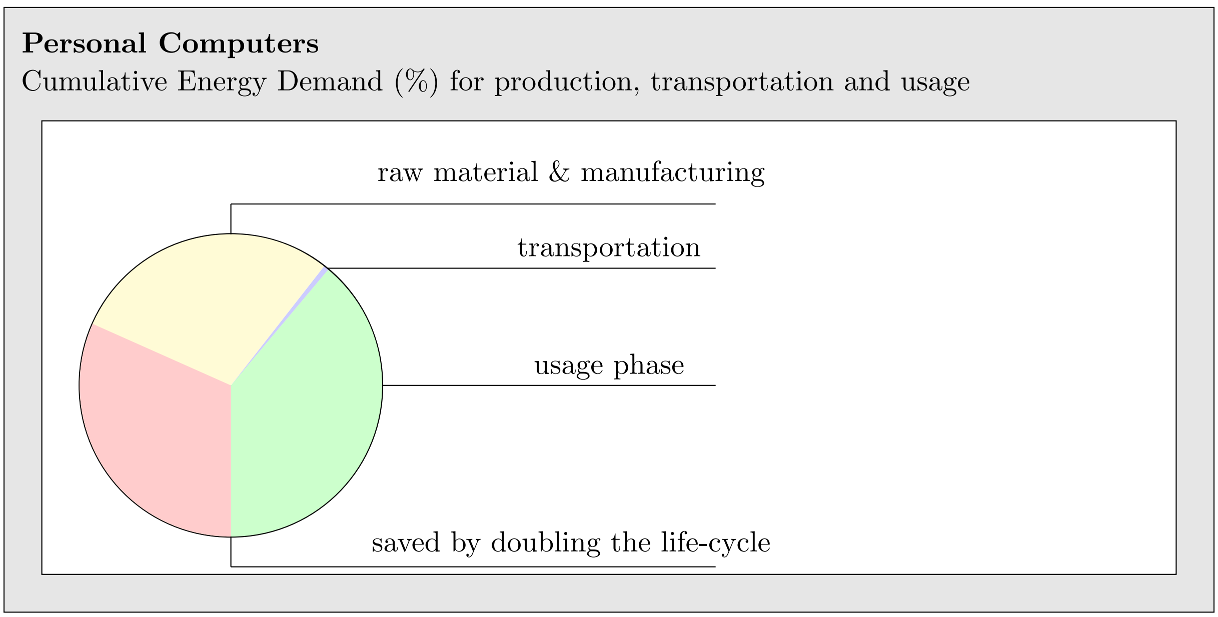

Figure 3: Cumulative Energy Demand (%) for the different phases of the life cycle of a personal computer. Data for production and usage obtained in Gotthardt et al. [2005]. Transportation's environmental impact is estimated using BUWAL-250 data for transportation consumption. It is assumed a transport moment of $10.000 kg \cdot kg$.

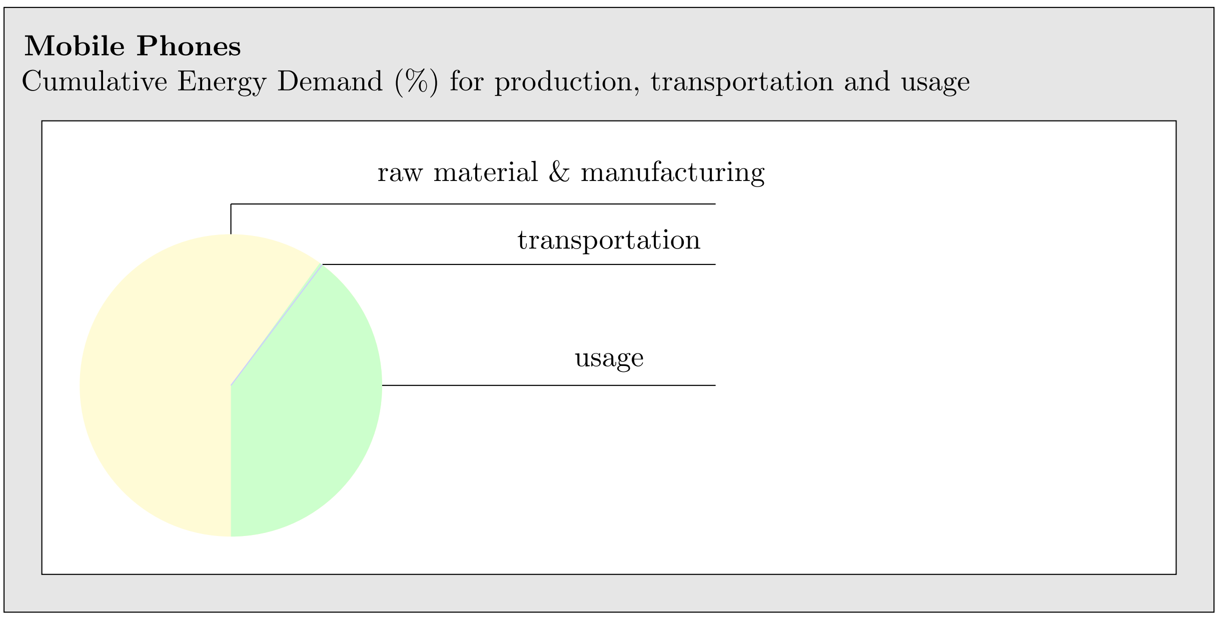

Figure 4: Cumulative Energy Demand (%) for the different phases of the life cycle of a mobile. Data for production and usage obtained in Gotthardt et al. [2005]. Transportation's environmental impact is estimated using BUWAL-250 data for transportation consumption. It is assumed a transport moment of $150 km \cdot kg$.

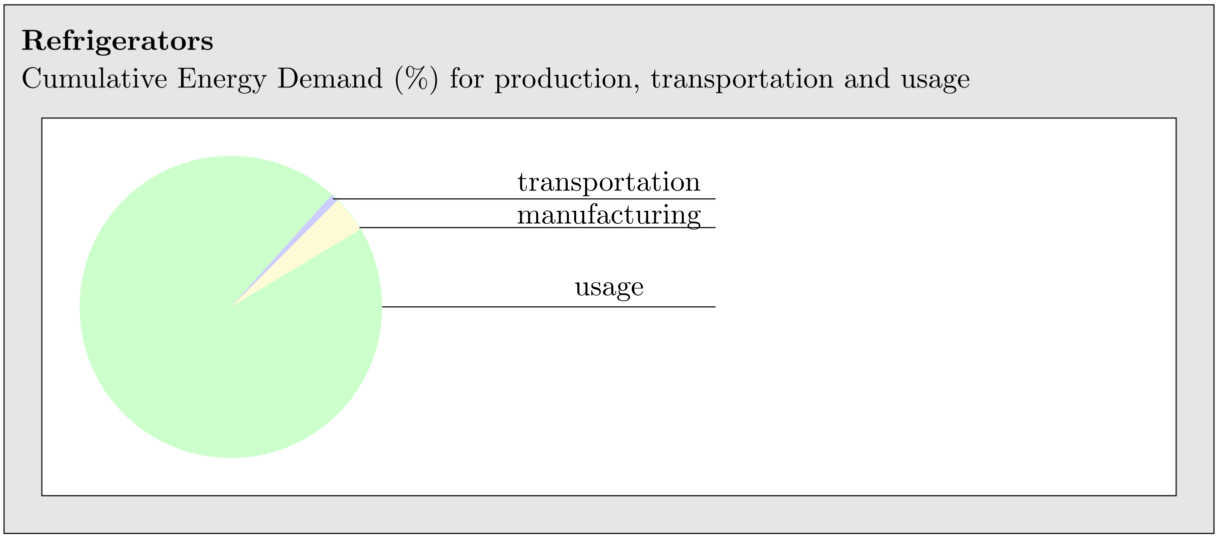

Figure 5: Cumulative Energy Demand (%) for the different phases of the life cycle of a refrigerator. Data from production and usage obtained in Williams [2005]. Transportation's environmental impact is estimated using BUWAL-250 data for transportation consumption. It is assumed a transport moment of $70,000 kg \cdot km$.

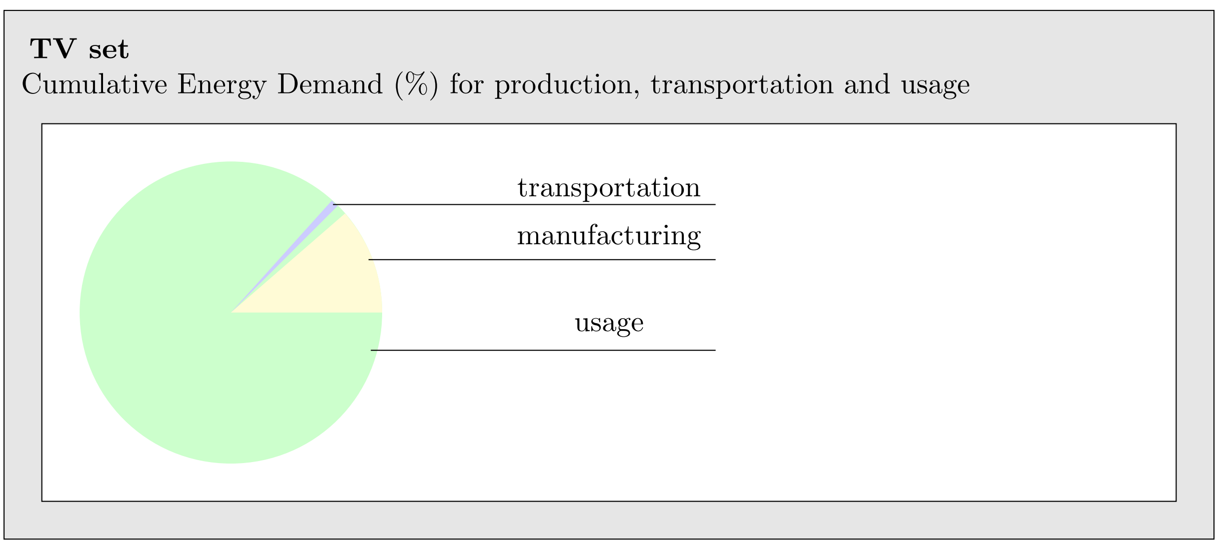

Figure 6: Cumulative Energy Demand (%) for the different phases of the life cycle of a tv set. Data from production and usage obtained in Behrendt et al. [1997].

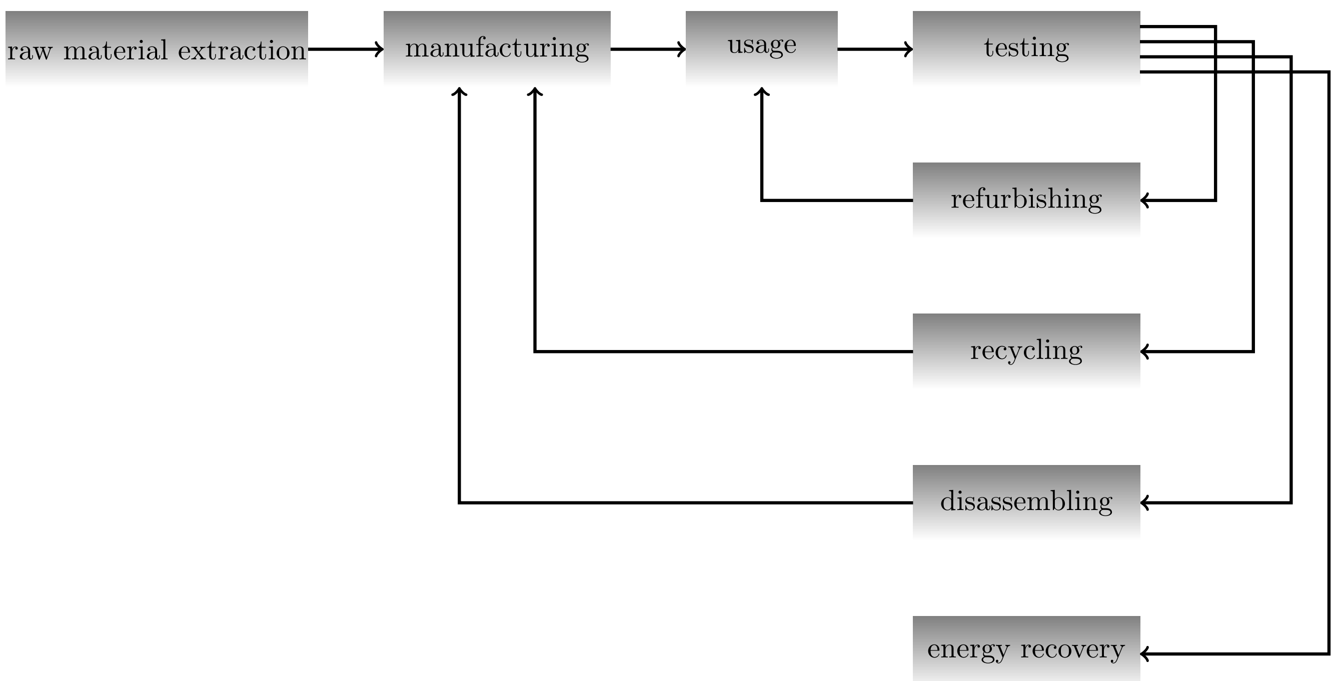

Figure 7: Main Activities Influencing Costs and Environmental Impact in Logistic Networks.Transportation is represented by the arcs.

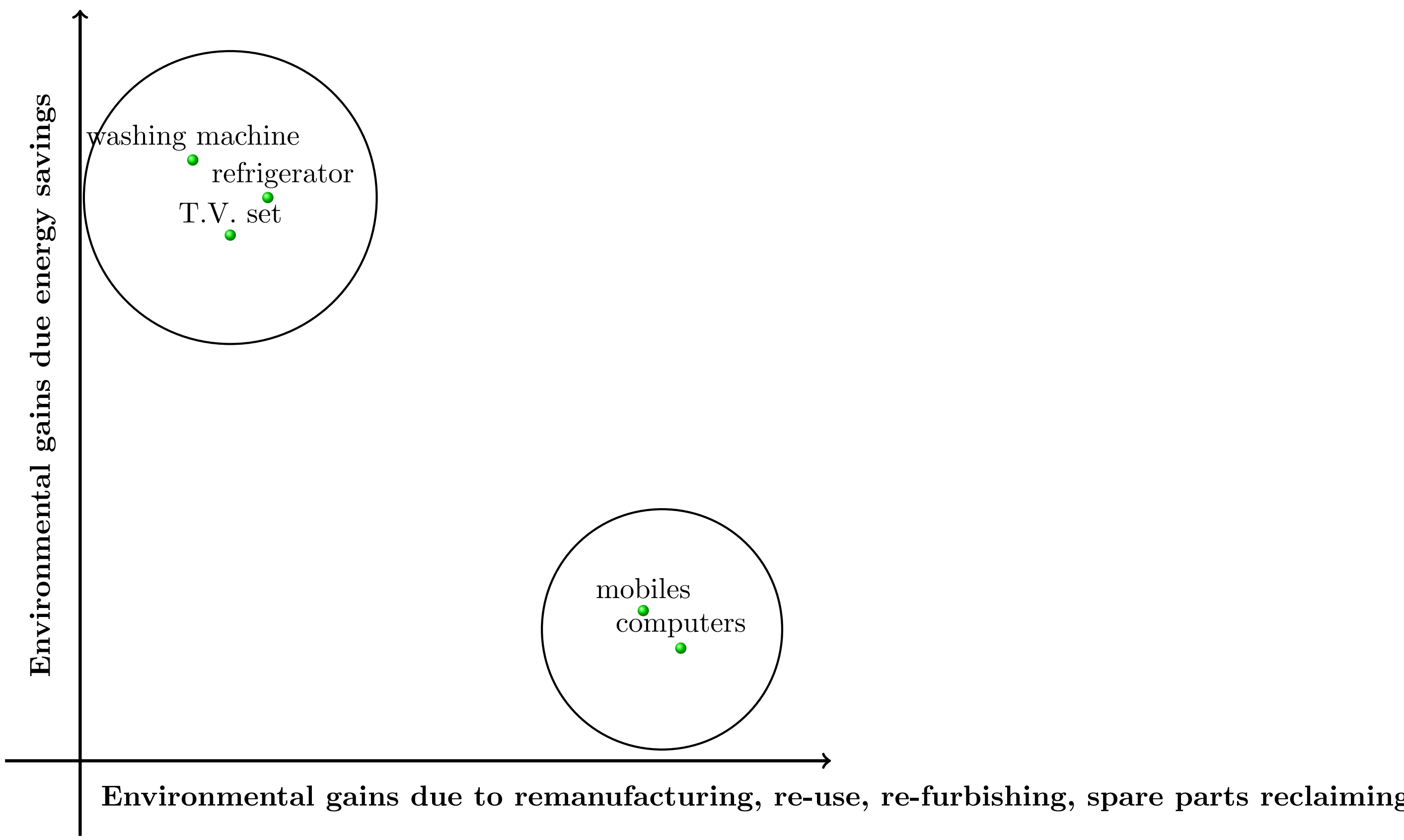

Figure 8: Environmental gains for EEEs due to recycling,re-manufacturing and re-use as well as energy consumption reduction

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