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ERIM REPORT SERIES *RESEARCH IN MANAGEMENT*	
ERIM Report Series reference number	ERS-2006-075-LIS
Publication	October 2006
Number of pages	30
Persistent paper URL	
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Address	Erasmus Research Institute of Management (ERIM) RSM Erasmus University / Erasmus School of Economics Erasmus Universiteit Rotterdam P.O.Box 1738 3000 DR Rotterdam, The Netherlands Phone: + 31 10 408 1182 Fax: + 31 10 408 9640 Email: info@erim.eur.nl Internet: www.erim.eur.nl

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REPORT SERIES
RESEARCH IN MANAGEMENT

ABSTRACT AND KEYWORDS	
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Free Keywords	Recycling logistics network, Environmental impacts, Profitability, Eco-efficiency
Availability	The ERIM Report Series is distributed through the following platforms: Academic Repository at Erasmus University (DEAR), DEAR ERIM Series Portal Social Science Research Network (SSRN), SSRN ERIM Series Webpage Research Papers in Economics (REPEC), REPEC ERIM Series Webpage
Classifications	The electronic versions of the papers in the ERIM report Series contain bibliographic metadata by the following classification systems: Library of Congress Classification, (LCC) LCC Webpage Journal of Economic Literature, (JEL), JEL Webpage ACM Computing Classification System CCS Webpage Inspec Classification scheme (ICS), ICS Webpage

A methodology for assessing eco-efficiency in logistics networks

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October 20, 2006

Abstract

Recent literature on sustainable logistics networks points to two important questions: (i) How to spot the preferred solution(s) balancing environmental and business concerns? (ii) How to improve the understanding of the trade-offs between these two dimensions? We posit that a complete exploration of the efficient frontier and trade-offs between profitability and environmental impacts are particularly suitable to answer these two questions. In order to deal with the exponential number of basic efficient points in the frontier, we propose a formulation that performs in exponential time for the number of objective functions only. We illustrate our findings by designing a complex recycling logistics network in Germany.

1 Introduction

In the past years, consumers, companies and governments have increased their attention towards the environment. Increased exposure in the media on environmental issues in conjunction with the escalating increase in the environmental resources depletion, human toxicity levels and ecosystem quality deterioration have made our entire society more aware of environmental damage. Companies, in turn, are investing more in the assessment of the environmental impact of their products

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and services, as well as in the reduction of such impacts. IBM, for instance, promotes the take-back, recycling, refurbishing and re-use of its computers (Fleischmann et al. [2003]). Governments have changed the *"end-of-pipe"* environmental laws to more comprehensive ones, broadening the responsibility of producers towards a *"cradle-to-grave"* perspective. The European Union, for instance, has approved the Waste Electrical and Eletronic Equipment (WEEE) directive, making producers responsible for their end-of-life products.

Improvement in environmental quality, however, does not come for free. The win-win solutions for business and the environment seem quite elusive in practice, in particular for considerable reductions on environmental pressure (Walley and Whitehead [1994]). The popular saying "there is no such a thing as a free lunch" could not be more true in this case. On the sphere of the "no free lunch" paradigm, some questions should be posed: How much will we have to spend in order to improve the environmental quality? Or in more scientific terms, what are the *trade-offs* between the environmental pressure of an economic activity and its costs? And what are the *trade-offs* for specific classes of environmental pressure or effects on humans and the ecosystem we live? Furthermore, what are the "best" solutions balancing ecological and economic concerns? (Quariguasi Frota Neto et al. [2007]).

On the normative and qualitative field, these questions have led to the concept of *trade-offs* and efficient frontiers for business and the environment (Huppes and Ishikawa [2005], Bloemhof-Ruwaard et al. [2004]). The rationale is to determine the set of solutions in which it is not possible to decrease environmental burn, or increase total environmental quality of each environmental category, unless increasing the costs. Figure 1 illustrates the efficient frontier and the *trade-offs*.

insert figure 1

From a methodological perspective, however, there is not much developed on determining such a frontier or assessing the *trade-offs* in sustainable logistics networks, despite the extensive existing literature in the field of multi-objective programming (MOP). We intend to bridge this gap by an approach that is sounded to capitalize the decision maker's most effective cognitive capabilities:

visual representation. In order to explore the efficient frontier in feasible CPU-time (for the intractability of determining all extreme efficient solutions in a multi-objective linear program, see Steuer [1994] and Steuer and Piercy [2005]), we develop a new algorithm to explore the Pareto frontier for multi-objective linear programming (MOLP) problems in which CPU-time grows exponentially only with the number of objective functions. The proposed approach can be used by companies to design their supply chains balancing their environmental footprint and the final cost of their products, or by governments to evaluate the effectiveness of environmental regulations.
The article is organized as follows: section two briefly reviews the main methodologies used to calculate eco-efficiency. Section three presents our proposed methodology, the eco-topology, as well as a presentation of the computational characteristics and the decision making process. We focus on the users' interaction in our approach, although the computational results are at least as interesting. Section four highlights the comparison between the existing methods and the one we propose. We clearly show the advantages of the latter over the formers. In section five we illustrate our method, as applied to the reverse logistics network of end-of-life Electrical and Electronic Equipment in Germany. Section six exposes the main pitfalls, limitations and further interesting research for our methodology. Section seven presents the conclusions.

2 A brief literature review on eco-efficiency

The idea of *"frontier"* for eco-efficiency was first presented in Huppes and Ishikawa [2005]. They also proposed the concept of an eco-frontier with the "optimum" or preferred solution defined by society. Independently, Quariguasi Frota Neto et al. [2007] presented a methodology to assess this frontier and the *trade-offs* between costs and a single environmental impact factor. The latter is, as far as we know, the first approach to quantitatively assess the *trade-offs* between business and the environment, as well as to explore the efficient frontier. The works of Bloemhof-Ruwaard et al. [2004] advocate the same approach: provide the decision maker with parts or the complete Pareto Efficient Frontier for economic and environmental objectives.

These are, however, exceptions. Literature has been focused on presenting a single indicator for eco-efficiency. To the best of our knowledge, no other formulation explores the *trade-offs* between environment and business, as well as the efficient frontier that determines these trade-offs. Hellweg et al. [2005] proposed a method based on the differences between environmental impact indices divided by the respective difference in associated costs for different projects. The methodology is only suitable for a discrete number of possible solutions. Scholz and Wiek [2005] propose a similar approach, also based on ratios. Using Data Envelopment Analysis (DEA), Kobayashi et al. [2005] also provide a single measure based on the radial projection of the decision making units (DMUs). The three papers share two common characteristics. First, they provide a single efficiency measure and implicitly assume that the solution with the best ratio is preferred. Second, they are applied to a discrete and small (compared to combinatorial optimization problems, that might involve millions of variables) set of possible solutions, mainly to the selection of projects or technologies. Figure 2 portrays the method. Note that the alternative black dots, i.e. representing different projects or technologies, serve as inputs for the model. The frontier itself does not map a real solution, in this case.

insert figure 2

insert figure 3

Under an Operations Research and Life-Cycle Analysis perspective, Krikke et al. [2003] use weights to explore the efficient solutions in terms of the environment and business. They rely on the assumption that a weighting process captures the preferred solution for business and the environment. Figure 3 illustrates such procedure. Note that in this case, the black dots are outputs of the proposed model. Note also that different sets if weights may lead to an unbalanced exploration of the efficient frontier, with some regions being well explored while others are left completely untouched. Unless we use an alternative algorithm to calculate the weight indifferent regions, there is no other theoretical solution for this problem.

insert figure 4

The two *"families"* of formulations do not address the exploration of the efficient frontier or the respective calculation of *trade-offs*. The assumptions for decision making are that the eco-efficient ratio or the weighting procedure captures the preferred solution(s).

A third formulation is proposed by Quariguasi Frota Neto et al. [2007] via multi-objective programming. The formulation is equivalent to the second "family" of models, in the sense that it provides the same subset of solutions. For problems with a single environmental impact index, (thus bi-objective), it also provides alternative solutions, based on the convex combination of the extreme efficient points. Furthermore, for a single environment impact index, this approach gives a visual impression of the *trade-offs*. The approach is, however, impractical for problems with thousands of variables, as the number of solutions exponentially increases with the size of the problem. Figure 4 illustrates the results of such approach.

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

Quariguasi Frota Neto et al. [2007] was the first approach to define the theoretical frontier of Huppes and Ishikawa [2005]. A cradle-to grave approach is used to determine the eco-efficient frontier regarding business and the environment for the design of sustainable logistics networks. In this work, the diverse phases of a product: raw material extraction, manufacturing, transportation, use and end-of-use alternatives are accounted to determine the optimal solutions. In order to assess the trade-offs and determine the optimum configurations, multi-objective programming is used. A multi-objective programming is denoted by (Steuer and Piercy [2005]):

$$max\{c^1 x = z_1\}$$

$$...$$

$$max\{c^k x = z_k\}$$

$$s.t.\{x \in R^n \mid Ax \leq b, b \in R^m, x \geq 0\}$$

where k is the number of objectives. A point $\hat{x} \in S \subset R^n$ is *efficient* if and only if there is no $x \in S$ such that $c^i x \geq c^i \hat{x}$ and there is at least one $c^i x < c^i \hat{x}$. The *efficient set* or *efficient frontier* is the set of all efficient solutions.

In our formulation (see section 5), $c^1 x$ represents total profit of a certain configuration, $c^2 x$ the cumulative energy demand , $c^3 x$ the respective waste landfilled. The coefficients of the second and third objective function are obtained via Life Cycle Analysis (LCA), a standard technique for evaluating environmental impact.

Solving the MOLP problem, or finding every extreme efficient solution has two major drawbacks. The first concerns CPU-time. Steuer [1994], Steuer and Piercy [2005] and Papadimitrou and Yannakakis [2001] present computational difficulties in completely exploring the efficient frontier. For problems bigger than small examples computational time will be an issue. One way to overcome the problem is to interactively explore points on the frontier [1]. The drawback of such a formulation is that complete regions of the frontier may stay completely unexplored, as this approach does not ensure the number of efficient solutions found or the distance between them. The second drawback regards the visualization and interpretation of results. Dividing the environmental impact to three or more subcategories would lead us to a frontier which, besides being very difficult to completely define, is not possible to visualize.

In order to overcome these problems, we propose a new method to explore the efficient frontier, for a MOLP. We call this method eco-topology. The term designates a set of piecewise linear frontiers, named iso-pretium, in which it is possible to change *trade-offs* between environmental impact classes or respective impacts, i.e. human toxicity and eco-toxicity, while maintaining the same costs. The objective in this formulation is to provide the decision maker with the flexibility to determine his preferred target without the use of interactive processes or weight setting. The

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

algorithm performs in $O((\frac{1}{\rho})^{d-1} \times n^6)$, so computational time grows exponentially with the number of objective functions only. The frontier is constructed as follows, for our problem to minimize two environmental impacts (z_2 and z_3) and maximize profit (z_1) of a reverse logistics network:

1. Calculate the $max\{z_1\}$, $min\{z_2\}$, $min\{z_3\}$ and check the existence of $z_1 = 0$

2. For $i = 1$ to $\frac{1}{\epsilon}$ do

    $\hat{z}_1 = max\{z_1\} \cdot \epsilon \cdot i$

    $\dot{z}_2 = min\{z_2 \mid z_1 = \hat{z}_1\}$ and $\dot{z}_3 = min\{z_3 \mid z_1 = \hat{z}_1\}$,

    $\ddot{z}_2 = min\{z_2 \mid z_1 = \hat{z}_1 \ \wedge \ z_3 = \dot{z}_3\}$

    $\ddot{z}_3 = min\{z_3 \mid z_1 = \hat{z}_1 \ \wedge \ z_2 = \dot{z}_2\}$

    3. For $j = 1$ to $\frac{1}{\epsilon}$ do

        $\hat{z}_2 = \dot{z}_2 + (\ddot{z}_2 - \dot{z}_2) \cdot \epsilon \cdot j$

        $\hat{z}_3 = \{min\ z_3 \mid z_1 = \hat{z}_1 \ \wedge \ z_2 = \hat{z}_2\}$

        $F \leftarrow (\hat{z}_1, \hat{z}_2, \hat{z}_3)$

    end do

end do

4. Connect lexicographically pairwise the $f \in F$ with the same profit

5. end

where:

z_1 is the first objective function: marginal revenue of the network

z_2 is the second objective function: cumulative energy demand,

z_3 is the third objective function: landfilled waste,

ϵ is an auxiliary variable: the smaller this variable the higher the number of points on the frontier that are explored, and therefore the better the representation of the frontier.

F is the set of solutions for our formulation

In order to prove that the algorithm works we have to prove that there will always be at least one solutions for each $\hat{z}_3 = \{min\ z_3 \mid z_1 = \hat{z}_1 \ \wedge \ z_2 = \hat{z}_2\}$, and that this solution is Pareto-Optimal.

We first proof the following lemmas:

Lemma 1: there is a solution $f \in F$ such that $f = (max\{z_1\} \cdot \epsilon \cdot i, \mathring{z}_2, \mathring{z}_3)$ for every $0 < i < \frac{1}{\epsilon}$, where $\mathring{z}_2$, $\mathring{z}_3$ are values of z_2 and z_3.

Proof: If there are two solutions $(max\ \{z_1\}, z_2', z_3')$ and $(0, z_2'', z_3'')$ of a LP, where z_2', z_2'', z_3', z_3'' are values of z_2 and z_3, respectively, the convex combination of those two solutions is a feasible solution.

Lemma 2: if $min\{z_2\}$ and $min\{z_3\}$ exist, all efficient solutions of the original problem with the constraint $z_1 = \hat{z}_1$ are linear combinations of $(\hat{z}_1, \dot{z}_2, 0)$, $(\hat{z}_1, 0, \dot{z}_3)$, $(\hat{z}_1, \dot{z}_2, \ddot{z}_3)$ and $(\hat{z}_1, \ddot{z}_2, \dot{z}_3)$.

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

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

The figure 5 illustrates the algorithm.

insert figure 5

The solutions F are not necessarily Pareto-optimal regarding the original MOLP, due the constraint $z_1 = \hat{z}_1$, but they are Pareto-optimal for the original problem plus constraint $z_1 = \hat{z}_1$. The model could also incorporate another step to test the solutions in F for Pareto optimality. In our case study we test them "a posteriori", and differentiate in the graphical representation the Pareto-optimal from the non Pareto-optimal. The objective is to lock out non Pareto-optimal solutions, allowing the decision maker to identify them, as well as allowing a visual representation of the parts of the frontier in which win-win situations are still possible.

4 Comparison between Eco-topology and the existing methods

We compare the methodology with the three existing main trends in literature presented in section 2: 1) methods based on an single efficiency index, 2) methods based on weighting, aiming a partial exploration of the efficient frontier and 3) multi-objective methods based on the complete exploration of the extreme efficient vertices. We also draw parallels between the different methodologies.

The stream of research proposing a single efficiency measure is premised on the selection of one solution, out of a set of solutions, according to the highest $\frac{Economic\ Value}{Environmental\ Pressure}$ ratio. The main drawbacks of such formulation are: it is not possible to differentiate between different environmental impacts or to add new variables to the model, such as social aspects or performance levels. Furthermore, it does not give any information on the theoretical *trade-offs* between the dimensions of analysis (in our case business and planet). It also does not provide any flexibility to the decision maker to choose targets according to his most preferred solution. A high rate could, for example, be possible only via a cheap and environmentally unfriendly process; or alternatively, an extremely environmental friendly process with extremely high costs. Both could be undesirable, if not unrealistic. In mathematical terms, the ratio procedure is nothing but a DEA model with two variables and constant returns of scale. It can only be applied to a discrete set of alternatives. The eco-topology approach allows the decision maker to freely decide on the best *trade-offs* or location on the optimal frontier. It also allows an increment on the number of objectives, allowing discrimination between the different environmental pressure classes and the insertion of new variables, such as performance levels, for instance. The *trade-offs* between these variables can not only be determined but easily visualized via the iso-pretium curves. In the case of discrete solutions, the model should be adjusted for DEA formulations.

The second trend, partial exploration, is equivalent to an interactive version of the eco-curves. It is heuristic in the sense that it provides a subset of solutions contained in the eco-topology approach. First because it only explores the efficient vertices, but not the hyperplanes defined by these. Second because it does not completely explore, or at least it is not possible to ensure that all the extreme points are explored. The number of alternatives is then diminished. The weighting procedure is another drawback, since the weights may not correspond to their implicit importance. A weight of 70% for the environment does not necessarily mean a solution which takes more the environment into account, contrary to common belief. Furthermore, it is also not possible to determine any trade-off between the different dimensions analyzed.

The third approach is the one most closely related to the concept of the eco-topology as we present. In that "family", the objective is to completely explore the set of all efficient extreme solutions. This formulation gives the DM a set (in general with exponential size) of efficient solutions. In this case flexibility is given to the decision maker to decide out of the given number of alternatives. There is one serious drawback: it is known that it cannot be applied to big instances. An increase in the number of variables, therefore, may turn the problem unsolvable from a CPU-time perspective. The eco-topology is a polynomial time scheme, and its complexity grows exponentially with the number of dimensions in the problem only. The number of variables and constraints, however, grows polynomially. Furthermore, the set of alternatives is increased in the eco-topology method, and the visualization of the trade-offs is straightforward.

The main drawback of the proposed method is the computational complexity as compared to the weighting process. Compared to the other methods, maybe we can say the first has an "easy" interpretation of the results. We cannot think of any advantage of using the pure multi-objective approach.

This far we have not mentioned the articulated approach. In the articulated methods the Decision Maker interacts with the model until he finds a satisfiable solution. An example of such approach is the Pareto Race, or STEM , which promotes a "walk" on the facets of the frontier. For discrete problems, multi-attribute methods may also be used. We have found no literature on articulated methods for Eco-efficiency analysis, but it seems to be another fruitful area of research.

Table 1 describe the family of methods, their applicability, main advantages and limitations.

insert table 1

5 The German Waste Electrical and Electronic (WEEE) case

In the following, the algorithm described in Section 2.1 is applied to a real-world case study of recycling waste electrical and electronic equipment. Thereby, the applicability of the eco-topology method is shown, and the derivation of recommendations for decision-makers based on visualization of the results and calculation of trade-offs is demonstrated.

5.1 Description of the problem

According to the European Commission, the amount of waste electrical and electronic equipment (WEEE) is growing rapidly. Since WEEE contains hazardous as well as valuable substances, and must be treated properly, the directive of the European Parliament and the European Council on waste electrical and electronic equipment (WEEE-directive), dated 13th of February 2003 (WEEE-directive [2003]) is aimed at prevention, functional re-use, material recycling and energy recovery of WEEE in order to reduce the amount of waste that is disposed of.

It is the overall target of the directive to improve the environmental performance of all processes along the life cycle of electrical and electronic equipment, but the focus of this directive is laid on processes within the end-of-life-phase. Thus, systems for take-back and treatment of electronic products are to be implemented or existing systems are to be improved [Directive, 2003]. The directive is a mix of command-and-control and market driven instruments. Companies have to comply with the requirements of the legislation, and have absolutely no incentives to go further than the directive's obligations (the command-and-control part), but they are free to organize themselves in order to lower the costs of such a reverse supply chain (the market-based part). We intend to use the proposed algorithm to present the trade-offs between the amount of landfilling, direct focus of the WEEE, and the Cumulative Energy Demand (CED), an environmental impact index correlated to many other environmental impacts, such as Global Warming Potential. As an illustration of such trade-offs: reverse logistic providers are opening facilities in the Czech Republic, cutting treatment costs but increasing transportation and therefore Cumulative Energy Demand. The proposed approach can be used by companies to design their supply chains to balance their environmental footprint and the final cost of their products, or by governments, with further assumptions on companies' response (e.g. profit maximization) to evaluate the effectiveness of environmental regulations.

For our particular case study, we focus on the design of a logistics network for entertainment electronic equipment in Germany, including TVs, VCRs, stereos, etc. The final decision variables are the end-of-use of the mentioned electronic equipment and the final destination location. In other words, end-of-life and allocation decisions. Within the reverse logistics network systems, various tasks like acquisition and collection, transportation, sorting, disassembly, re-use, recycling and recovery of products, as well as storage and selling of material fractions are conducted as presented in figure 6.

insert figure 6

The collection of discarded electronic products from private households is organized by public waste disposal authorities, retailers or OEMs. After collection, products are transported to treatment companies. Treatment activities can aim at different goals - removal of harmful substances as well as gaining of valuable materials and reusable spare parts. After treatment, tradable material fractions of defined quality are sold or are disposed of. Metal fractions are supplied to metal or steel works for material recycling. Plastics are usually utilized for energy recovery.

A description of the arising allocation problem as well as the single-objective contribution margin maximization model with application to a real-world case study is given in Walther and Spengler [2005]. In the following, we expand this model to a multiple-objective one, thus taking not only the maximization of the contribution margin, but additionally the minimization of the Cumulative Energy Demand (Huijbregts et al. [2005]) and the minimization of the total amount of waste (target of the WEEE-directive) into account.

The objectives are, as presented before: (1) to maximize profit of the Network, (2) to minimize Cumulative Energy Demand, as well as (3) to minimize waste. Decision variables at each treatment company u are: masses of product i accepted from source $q(i^Q_{iuq})$, masses of product or material fraction i accepted from another treatment company $u'(y^U_{iu'u})$, number of executions of treatment activity $j(x_{ij})$, and masses of material fraction i delivered to recovery or disposal site $r(y^R_{iur})$.

$$\max \sum_{u=1}^{U}(\sum_{i=1}^{I}(\sum_{q=1}^{Q}(e_i^A - c^Q_{iqu}) \times y^Q_{iuq} + \sum_{u=1,u\neq u'}^{U}(-c^U_{iuu'}) \times y^U_{iuu'} + \sum_{r=1}^{R}(e^V_{ir} - c^R_{iur}) \times y^R_{iur}) - \sum_{j=1}^{J} x_{ju} \times c^Z_{ju}) \tag{1}$$

$$\min \sum_{u=1}^{U}(\sum_{i=1}^{I}(\sum_{q=1}^{Q} ced^Q_{iqu} \times y^Q_{iuq} + \sum_{u=1,u\neq u'}^{U} ced^U_{iuu'} \times y^U_{iuu'} + \sum_{r=1}^{R} ced^R_{iur} \times y^R_{iur}) + \sum_{j=1}^{J} x_{ju} \times ced^Z_{ju}) \tag{2}$$

$$\min \sum_{u=1}^{U}(\sum_{i=1}^{I}(\sum_{q=1}^{Q} y^Q_{iuq} - \sum_{r=1}^{R} y^R_{iur} \times rec_{ir})) \tag{3}$$

The output of a treatment company (y^D_{iu}) is given by the net result of all inputs of appliances from sources outside the network (y^Q_{iuq}), the input of appliances and material fractions from other treatment companies $(y_{iuu'})$, and the transformation of masses related to treatment. Latter is expressed as the number of executions of a treatment activity (x_{ju}) multiplied with an input-output-coefficient (v_{ij}) specifying the input-output-relationships of products and material fractions i of this activity j.

$$(\sum_{j} x_{ju} \times v_{ij}) + \sum_{q=1}^{Q} y^Q_{iuq} + \sum_{u=1,u\neq u'}^{U} y^U_{iuu'} = y^D_{iu} \qquad i = 1, ..., I; u = 1, ..., U \tag{4}$$

According to (5) the output of a treatment company (y^D_{iu}) is either delivered to recovery companies or disposal sites (y^R_{iur}) or to other (specialized) treatment companies $(y_{iuu'})$.

$$y_{iu}^{D} = \sum_{u=1,u\neq u'}^{U} y_{iuu'}^{U} + \sum_{r=1}^{R} y_{iur}^{R}, \qquad i = 1, ..., I; u = 1, ..., U \tag{5}$$

All products available at sources must be accepted and properly treated (6). Additionally, restrictions exist regarding treatment capacities at companies (7) and capacities at recovery and disposal sites (8).

$$\sum_{u=1}^{U} y_{iuq}^{Q} = y_{iq}^{QMAX}, \qquad i = 1, ..., I; q = 1, ..., Q \tag{6}$$

$$\sum_{j=1}^{J} c_{ju}^{z} \times x_{ju} \leq c_{u}^{ZMAX} \qquad u = 1, ..., U \tag{7}$$

$$\sum_{u=1}^{U} y_{iur}^{R} \leq y_{ir}^{RMAX} \qquad i = 1, ..., I \qquad r = 1, ..., R \tag{8}$$

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

$$y_{iuq}^{Q}, y_{iuu'}^{U}, x_{ju}, y_{iur}^{R}, y_{iu}^{D} \geq 0 \tag{9}$$

5.2 Application of the algorithm

In the following, the algorithm of Section 3.1 is applied to the WEEE case study. First, the profit (objective 1) is maximized ignoring all other objectives. In the WEEE case, the maximum attainable profit is 1.1 Mio.€/y if CED and waste are not taken into account. A certain number of isopretium curves is then calculated by multiplying the maximum profit with coefficients $\epsilon \cdot i$ for all $i = 1, ..., \frac{1}{\epsilon}$. Thus, each isopretium is representing a certain fraction of the maximum profit. In the WEEE case, 10 isopretium curves are calculated ($\epsilon = 0.1$), which means that the lowest profit isopretium curve (110,000 €/y) is representing 1/10th of maximum profit. For each of these ten fractions of the maximum profit, CED (objective 2) as well as waste (objective 3) are minimized separately. Doing so, the solution space is limited since unfeasible solutions (i.e. all results representing less then the minimum attainable CED and waste) can be eliminated for each isopretium curve. In the WEEE case for example, it is not possible to reach less than 5,700 GJ/y

CED and 2,380 t/y of waste if a profit of 220,000 €/y is at least aimed at. Keeping the profit as well as the minimal attainable CED unaltered, the minimal waste is now calculated. For a profit of 220,000 €/y and 5,700 GJ/y of CED this results in 5,830 t/y of waste . The same is done keeping the objective value of the profit as well as the minimal waste unchanged, which is for the example a profit of 220,000 €/y and waste of 2,380 t/y resulting in 8,940 GJ/y of CED. Note that there is a trade-off between CED and waste minimization in the WEEE case. Therefore, the minimization of CED and the minimization of waste each lead to maximum values for the other objective for a given profit. Applying these calculations, the solution space is bounded, and the starting and ending points of the isopretium curve are now known. Thus, the curve connecting these two points can be calculated. This is done by slowly raising the CED by a certain fraction $\epsilon \cdot i$ for all $i = 1, ..., \frac{1}{\epsilon}$, and each time calculating the minimized waste for this combination of maximized profit/minimized CED until the maximum CED (and thus in the WEEE case the minimum waste) is reached for this isopretium. The results are stored, and the algorithm is repeated by slowly raising the profit objective by $110,000$ €/y ($\epsilon\cdot$ maximum profit) until the maximum profit is reached.Figure 7 illustrate the search for a $220,000$ €/y isopretium.

insert figure 7

5.3 Results

The results of the iso-pretium curves are represented in figure 8. The curve ending on the right of the others represents the iso-pretium for a profit of 90% of the maximum profit, or $990,000$€/y. The one ending on the left of all other represents the iso-curve for a profit of 20% the maximum profit, $220,000$€/y. The curves in between represent, respectively 30%, 40%, 50%, 60%,70% and 80% of the maximum profit. The maximum profit (100%) has a single point (5,488t/y and 5,892GJ/y).

insert figure 8

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

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

Also worth noticing is the fact that the reduction in the amount of waste going to landfill due to decrease in the profitability of the supply chain is not much affected by the level of profitability or CED. For a cost of $660,000$ €/y and a CED of $7,820$ GJ/y, a reduction in landfilling costs is approximately 1€/kg, maintaining the level of CED. In the same iso-pretium, and a CED of $7,180GJ/y$, the reduction in landfilling costs is approximately 1.3 €/kg. The result is robust for all iso-pretiums. For a profit of 330,000€/y and a CED of 8,620 GJ/y the reduction in landfilling is 1.4 €/kg. The cost for reduction in landfill is 2€/kg for a 8,620 GJ/y CED . The values are quite high compared to normal take-back prices. A 12kg computer would cost between 12€to 20€. Looking at the results for shadow-price of CED, one can note that they rapidly increase with the increase in profitability. From iso-pretium with profit of 330,000 €/y to iso-pretium with profit of 220,000€/y at a 8,620 GJ/y CED, the unitary reduction costs 0.12€/MJ. The same reduction from iso-pretium with profit of 880,000 €/y to 770,000 €/y results in unitary cost of 0.46 €/MJ for a 6,710 GJ/y CED. Both results seem quite high: buying the comparative amount of carbon credit would cost 0.003€/MJ (Carbonfund-Organization [2006]).

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

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

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

6 Conclusions and Outlook

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

In this paper we focus on the exploration of the eco-topology concept for the MOLP. Quite some problems regarding eco-efficiency can be modeled as such. Examples of papers for allocation and end-of-use decisions are presented in Bloemhof-Ruwaard et al. [1996] and Walther and Spengler [2005] for the linear case. Other problems that can still be tackled by our methodology are those regarding disassembly decisions (see Lambert [1999] and Lambert [2003]).

The model can also be extended to combinatorial problems, but some remarks are worth to be made. First, problems that cannot be ϵ-approximated cannot be modeled: if you can't find one single approximation for the problems, you can't find a set(Papadimitrou and Yannakakis [2001]). It eliminates, therefore, the whole class of APX-hard problems. For models including decisions regarding the location-allocation of end-of-use facilities (i.e. recycling, refurbishing, etc.) such as in Fleischmann et al. [2000] and Krikke et al. [2003] no such ϵ-approximation is possible. An alternative for such problems is to determine the solution and then compare this solution with a relaxed solvable form. For more on ϵ-approximation of combinatorial multi-objective problems see Papadimitrou and Yannakakis [2001]. Second, on dealing with combinatorial problems, it is clear that such a thing as a frontier does not exist. In case we define such frontier as in DEA, notice that convexity will be lost due to the unsupported solutions.

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

7 Table and Figures

Indices and Sets:

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

Decision variables:

y_{iqu}^{Q}	mass of discarded product type i delivered from collection point q to recycling company u
y_{iur}^{R}	mass of material type i delivered from recycling company u to recovery/disposal facility r
x_{ju}	number of executions of recycling operation j in recycling company u
$y_{iuu'}^{U}$	mass of discarded product type i delivered from recycling company u to recycling company u'

Parameters:

v_{ij}	recycling operation coefficient representing input(-)/output(+) masses of product/material type i consumed/caused by one execution of recycling operation j
e_{i}^{A}	acceptance fees, the network gets for treating one kilogramme of product type i

c^Q_{iqu} costs for transportation of one kilogramme of material type i from collection point q to recycling company u

$c^U_{iuu'}$ costs for transportation of one kilogramme of material type i from recycling company u to recycling company u'

ced^Q_{iqu} CED for transportation of one kilogramme of material type i from collection point q to recycling company u

ced^R_{iur} CED for transportation of one kilogramme of material type i from recycling company u to recovery/disposal facility r

$ced^U_{iuu'}$ CED for transportation of one kilogramme of material type i from recycling company u to recycling company u'

ced^Z_{ju} CED for recycling activity j at recycling company u

e^V_{ir} sales revenue(+)/disposal cost(-) for delivery of one kilogramme of material type i to recovery/disposal facility r

c^R_{iur} costs for transportation of one kilogramme of material type i from recycling company u to recovery/disposal facility r

c^Z_{ju} costs for the application of one recycling operation j in recycling company u

rec_{ir} fraction of material type i that was sent to recovery facility r approved to be recycled

y^{QMAX}_{iq} mass of product type i that has to be collected at source q

y^{RMAX}_{ir} capacity available at recovery/disposal facility r

C^{ZMAX}_u capacity available at recycling company u

ID	Family	papers	trade-off?	Flex.?	C. Class?	Visual Trade-off?
1	Single Ratio	Kuosmanen and Kortelainen [2005] Hellweg et al. [2005] Scholz and Wiek [2005] Kobayashi et al. [2005]	NO	NO	-	NO
2	weighting LP	Bloemhof-Ruwaard et al. [2004] Krikke et al. [2003]	NO	YES	P	NO
3	Multi-objective	Quariguasi Frota Neto et al. [2007]	YES/NO	YES	NP-hard	YES/NO
4	Eco-Topology	-	YES	YES	FPTAS	YES

table 1: Main streams of research on eco-efficiency

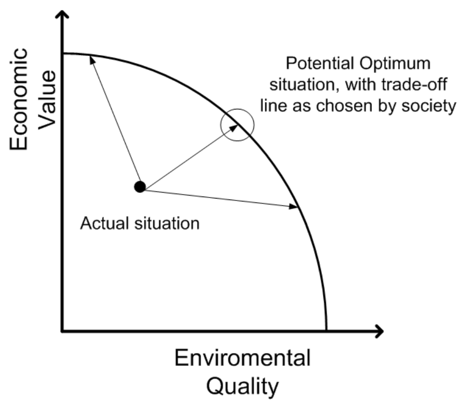

Figure 1: Eco-efficiency in society: Actual technologies and production possibility envelope. Adapted from Huppes and Ishikawa [2005].

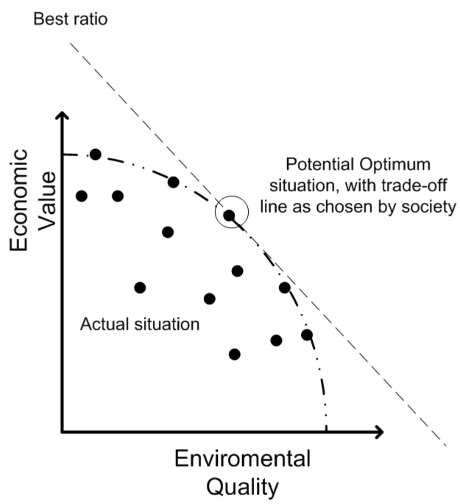

Figure 2: The single ratio Methods

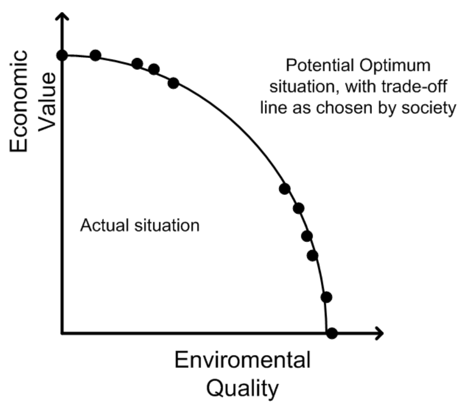

Figure 3: The weighting method (also called Preference Structure Method)

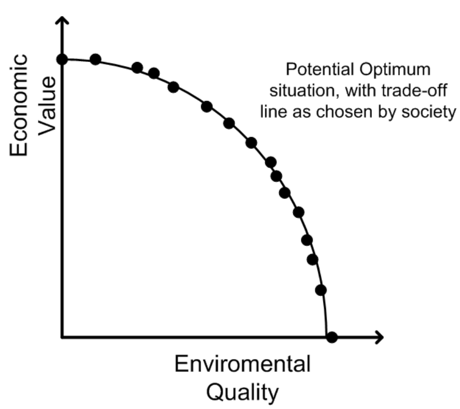

Figure 4: Pareto Optimal Frontier

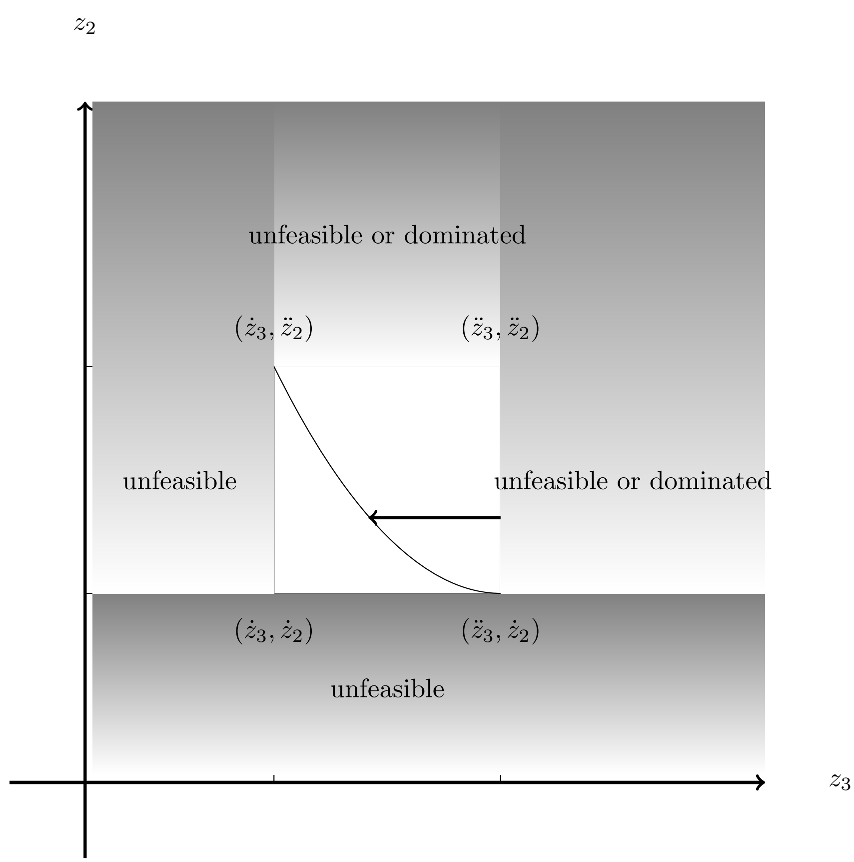

Figure 5: The proposed search for equally dispersed pareto-efficient solutions

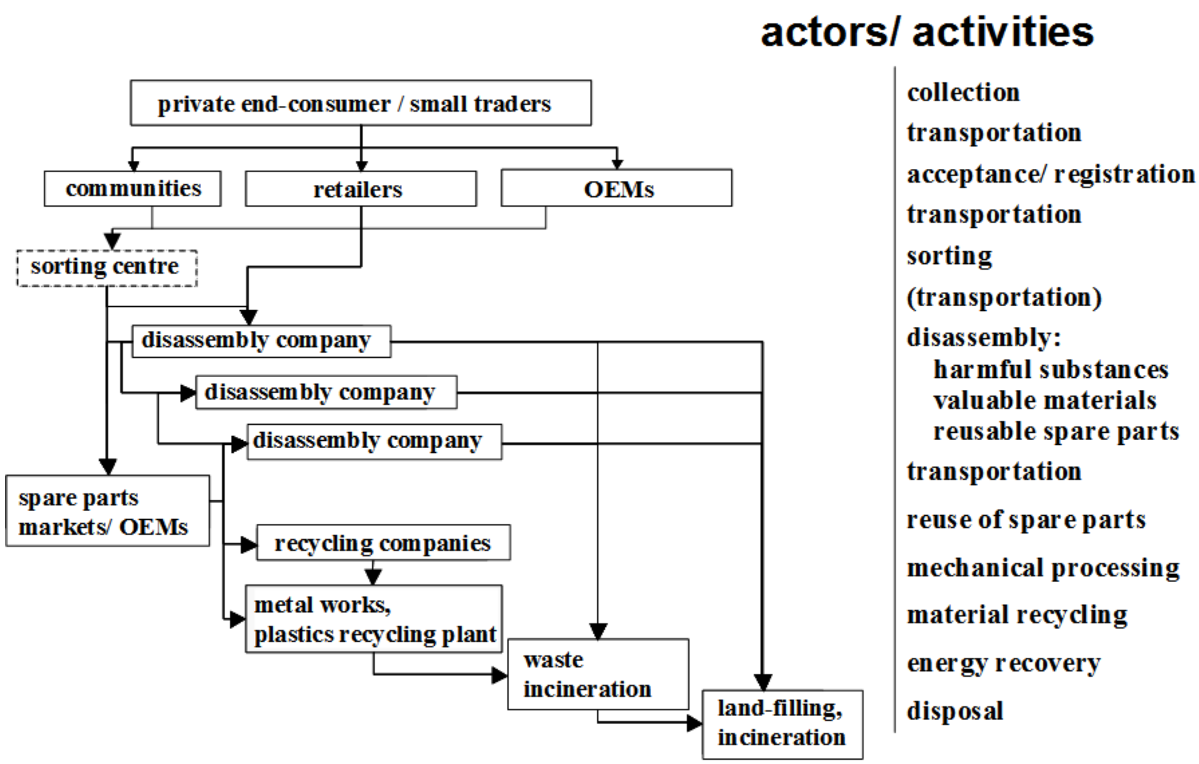

Figure 6: Actors and activities within the field of WEEE treatment

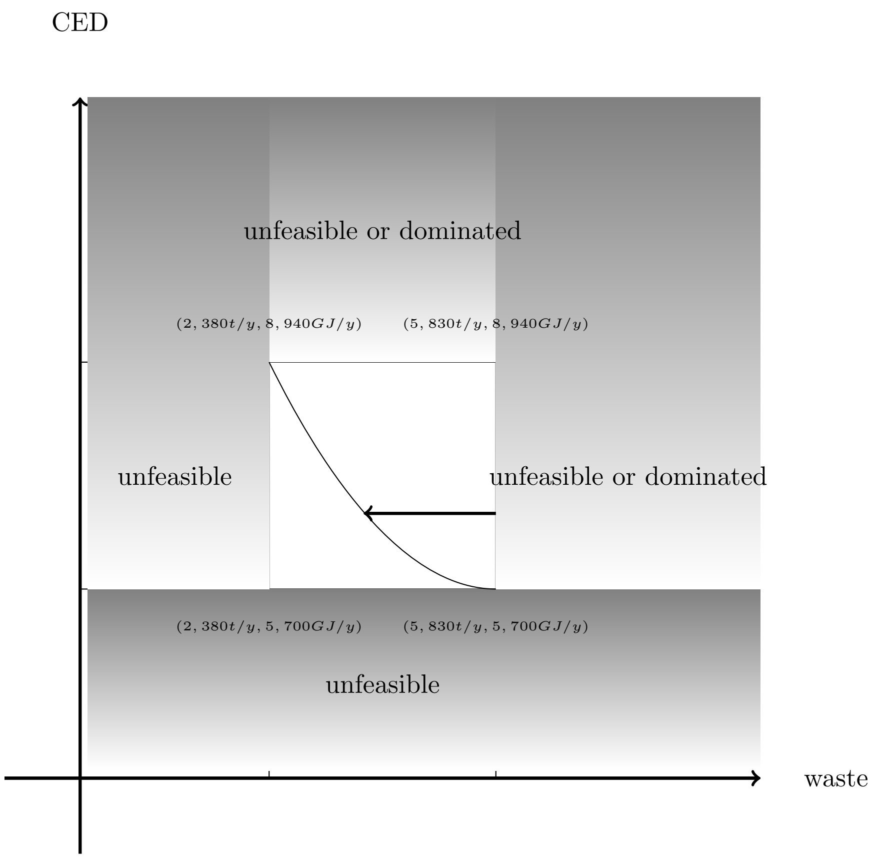

Figure 7: The proposed algorithm for a 220,000 € isopretium

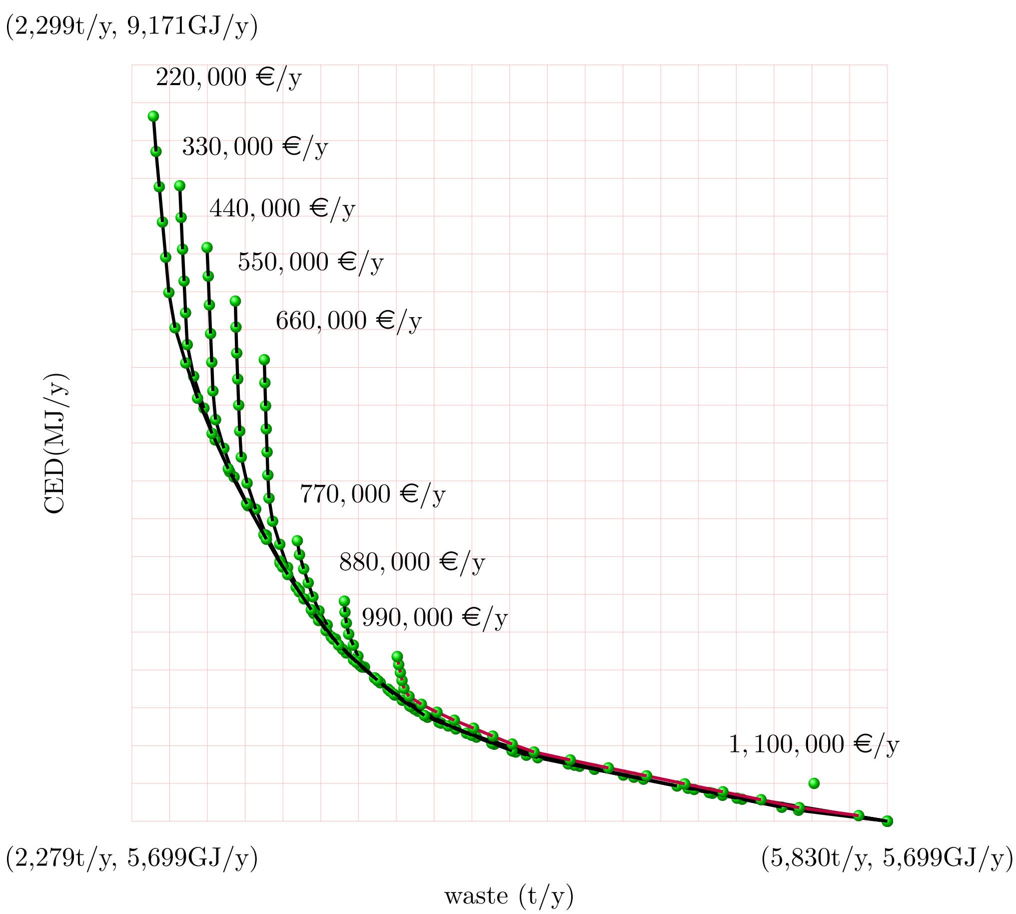

Figure 8: Eco-efficient frontier. The pairs (a,b) are, respectively, the landfilled waste and CED. The number at the end of the lines are profit for the isopretiums.

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