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Eco-Efficiency of Electric and Electronic Appliances: A Data Envelopment Analysis (DEA)

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Abstract Several papers have studied the eco-efficiency of manufacturing systems to address strategic socioeconomic issues in the context of sustainability analysis. Their goal has been to take into account not only environmental impact aspects throughout the whole life cycle but also to incorporate the associated economic value as well, thus, giving a comprehensive vision of both factors. This paper focuses on different commonplace household electric appliances, comparing their eco-efficiency computed using a data envelopment analysis model. We consider the retail price as a measure of the product's economic value and the ecopoint LCA score as the assessment of its environmental impact. We conclude that cell phones and the bulky analyzed appliances have the highest eco-efficiency scores, whereas the rest would require a more environmentally friendly redesign and/or an increase in their perceived value to improve their eco-efficiency.

Keywords Eco-efficiency · LCA · Data envelopment analysis (DEA) · Electric and electronic waste · Recycling

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1 Introduction

The production and consumption of electrical and electronic equipment has increased exponentially in recent years. According to Cui and Forssberg [5], the production of electrical and electronic equipment (EEE) is one of the fastest growing areas. In the former 15 European Union member countries, the amount of electric and electronic waste produced each year varied between 3.3 and 3.6 kg per capita for the period 1990–1999 and has been projected as 3.9–4.3 kg per capita for the period 2000–2010 [9]. This can be considered a real threat to human health and the environment [32] and has resulted in new legislation that ensures that the waste is treated in as environmentally friendly a way as possible. The main goal of this legalization is the obligation to take back all equipment after use for treatment. These new laws entail the creation of new logistic networks for collecting all these appliances and have increased the interest in the end-of-life of these products.

Governments and many customers simply expect companies to pay proper attention to the environmental properties of all their products. EMAS, BS and ISO 14000 series call for continuous improvement in environmental management systems, and companies must seek products that are also from an environmental point of view.

The concept of *eco-efficiency* dates back to the nineties [23, 30] and constitutes an instrument for sustainability analysis [16], its goal being to maximize the economic value of the product while minimizing its environmental impact (use of resources and emissions). It is usually expressed as the ratio of product value divided by its environmental burden [37]. This ratio is also called environmental productivity or incremental eco-efficiency in Huppes and Ishikawa [16]. Therefore, the way to increase eco-efficiency is to reduce the environmental impact of the product or to increase its economic value. Jointly considering both environmental and economic factors effectively addresses the question of how production volume affects environmental impact, something that traditional assessment techniques were not able to consider.

According to Michelsen et al. [22], the two most important applications of eco-efficiency are as an internal tool for measuring system progress and for communicating economic and environmental performance. For Huppes and Ishikawa [16], eco-efficiency is an instrument for sustainability analysis. Note should be taken, however, that there are also some authors who are critical of the eco-efficiency concept (see Erkko et al. [10] for a review).

Whatever the case may be, an important problem with constructing eco-efficiency indicators is that there are no agreed rules or standards for recognition, measurement, and disclosure of environmental information [36]. However, it is very important to define how to measure the economic and impact values of a product. Dyckhoff and Allen [8] suggest using life cycle assessment (LCA), a well-established technique [13, 35], to determine environmental indicators across a number of impacts categories. Michelsen et al. [22] use LCA to assess the environmental performance and cumulative costs of a product over its life cycle as a measure of its economic value. Kuosmanen and Kortelainen [20] use measures of environmental pressures computed by weighting the contribution of different pollutants and unit profit as a measure of economic value added. Kuosmanen and Kortelainen [21] also use environmental pressures, but instead of computing a ratio, use absolute shadow prices so that a net economic value is computed as value added minus environmental costs. These papers use data envelopment analysis (DEA), also a well-established methodology [4, 33], to compute eco-efficiency scores. More specifically, DEA is a non-parametric linear programming (LP)-based technique commonly used to assess the relative performance of a set of units. Each unit is assumed to consume certain amounts of inputs to produce certain amounts of outputs. DEA identifies non-dominated (i.e., efficient) units and, for those found to be inefficient, provides both an efficiency score and target values for inputs and outputs. The larger the possible reduction in inputs and the increase in outputs, the lower the efficiency score.

In the present comparative study, with respect to economic value, we add all the production and logistic costs using the retailing price (what the user is willing to pay) as a measure of product value. As for environmental impact, LCA will provide us with "ecopoints" as a unit of measure for this impact. The proposed approach assesses selected electric and electronic appliances using a standard DEA model that considers the overall environmental impacts computed by LCA as inputs and the retail price as output. We aim to assess how eco-friendly these products are from a value-versus-environmental-impact point of view. The idea underlying the proposed approach is that consumer behavior might be affected, at least in the medium term, by the information of the relative eco-efficiency of products, although such assessment is not static but evolves with time.

The manuscript layout is as follows: in Section 2 we present the appliances considered and how LCA was used to calculate the ecopoints that measure their environmental impact; Section 3 presents the DEA model, whereas Section 4 shows the results of applying the model to the selected sample of EEE products; Section 5 summarizes the main conclusions and relevant findings obtained in this study.

2 Environmental Impact Assessment of Household Appliances

Consumers discard a wide variety of household appliances, often in different ways depending on their size, with small items being easier to dispose of than larger ones. For this reason and to take into consideration a wide spectrum of products, we focused our analysis on nine different commonplace items, presenting different technologies, weights, and sizes. The selected products were: a washing machine, a fridge, a TV set, a cell phone, a desktop computer, a coffee machine, a vacuum cleaner, a hair dryer, and an iron.

To assess their environmental impacts, it is first necessary to account for the inventory of all the materials that make up each product. With that purpose in mind, different sources were explored (from manufacturers' web pages to data gathering from direct examinations after disassembling) to obtain the composition of an average appliance of each type. A summary with the list of the most important components is presented in Table 1. The figures between brackets refer to percentages by weight.

LCA is a methodology used to assess the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment and to evaluate and implement opportunities to effect environmental improvements [31]. LCA encompasses all the different steps in the life cycle of goods: extraction and processing of raw materials, manufacturing, transportation, distribution, use, reuse, maintenance, recycling, and final disposal.

According to ISO standards, this methodology consists of four phases: goal definition and scope, inventory analysis, impact assessment, and interpretation [17, 18]. Goal definition and scope determine the point of view and the guidelines that will be followed during the rest of the study; inventory analysis involves gathering data relative to

Table 1 Inventory data for the selected appliances (weights in grams or kilograms, and percentages of total weight between brackets)

Components	Washing machine[a] (60.5 kg)	Fridge[b] (40 kg)	TV set[c] (15.6 kg)	Cell phone[d] (114 g)	Computer[e] (23 kg)	Coffee machine[f] (3 kg)	Vacuum cleaner[g] (4.5 kg)	Hair Dryer[h] (540 g)	Iron[i] (1.15 kg)
ABS					3.40 (14.78)		0.27 (6.00)	300 (55.56)	0.35 (30.41)
Aluminium	1.21 (2.00)	1.98 (4.94)	0.16 (1.00)	2.28 (2.00)	0.32 (1.40)	0.6 (20.00)	0.81 (18.00)	40 (7.41)	0.50 (43.44)
Bronze					0.04 (0.17)				
Cardboard					3.60 (15.65)				
Concrete	24.20 (40.00)								
Copper		0.32 (0.81)	0.47 (3.00)	14.82 (13.00)	1.42 (6.18)	0.1 (3.30)	0.675 (15.00)	70 (12.96)	0.04 (3.48)
Epoxy resin				13.68 (12.00)					
Glass		0.34 (0.86)	7.80 (50.00)	19.38 (17.00)	3.60 (15.65)	0.5 (16.70)			0.001 (0.09)
Iron	16.94 (28.00)	25.66 (64.14)	1.72 (11.00)	4.56 (4.00)	7.62 (33.11)			80 (14.81)	
Lead				0.57 (0.50)	0.05 (0.23)				
Magnesium				2.28 (2.00)					
Nickel				1.71 (1.50)	0.10 (0.43)				
Oil and CFC		0.33 (0.83)							
Other Materials			1.87 (12.00)						
Paper							0.045 (1.00)		
Phosphorus			0.16 (1.00)						
Plastic	6.05 (10.00)	4.84 (12.09)	3.43 (22)						
Polypropylene					1.22 (5.29)	1.5 (50.00)	0.9 (20.00)	10 (1.85)	
Polycarbonates					0.55 (2.37)				
Polystyrene				30.78 (27.00)			0.45 (10.00)		
Polyurethane		5.93 (14.83)							
PVC				9.12 (8.00)	0.86 (3.75)	0.15 (5.00)	0.45 (10.00)		
Rubber					0.03 (0.12)		0.09 (2.00)		0.01 (0.87)
Silicon				12.54 (11.00)	0.02 (0.07)				
Steel (stainless)	10.29 (17.00)					0.15 (5.00)	0.765 (17.00)	40 (7.41)	0.25 (21.72)
Textile							0.045 (1.00)		
Tin plate				0.57 (0.50)	0.08 (0.34)				
Water with R11		0.60 (1.50)							
Wood	1.82 (3.00)								
Zinc				1.71 (1.50)	0.10 (0.44)				

[a] DARP Environmental (2005) *WEE Remarket project: investigation into the remanufacturing and reuse of white good parts*, internal report; frontal charge, 601×600×850 mm
[b] www.mitsubishi.com; one-door fridge; two models: 85×55×50 cm and 200×70×60 cm
[c] www.mitsubishi.com; classical TV set, non-LCD technology
[d] www.mitsubishi.com
[e] Microelectronics and Computer Technology Corp. (1996), Electronics Roadmap, Austin, TX; non-LCD monitor
[f] Simapro 6.0
[g] http://europa.eu.int/comm/environment/ecolabel/pdf/vacuum_cleaners/finalreport_vacuum_july2002.pdf
[h] personal experimentation performed by authors
[i] personal experimentation performed by authors

inputs and outputs at each stage of the product life cycle, whereas the aim of impact assessment is to interpret this data in terms of environmental impacts (ISO 14042). Finally, these results are interpreted according to goal definition and scope in the interpretation phase [27].

To carry out this analysis and obtain the data of each impact category, the computer application SimaPro 6.0 [25] was used. This program allows the environmental impacts of a system to be analyzed and compared both systematically and consistently. Of the several methods of assessment that can be used in SimaPro, we considered Eco-Indicator 99 as the most suitable method to analyze the obtained results. Previous authors such as Tsilingiridis et al. [34] or Raluy et al. [26] have used the same indicator, proving that this method is comprehensive and provides indices for many data categories.

Eco-indicator 99 scores are based on an impact assessment methodology that transforms the data of the inventory table into three comprehensive damage scores: human health, ecosystem quality, and resources. The human health damage model has been developed for respiratory and carcinogenic effects, the effects of climate change, ozone layer depletion, and ionizing radiation [15]; the damage category ecosystem quality consists of ecotoxicity, acidification, eutrophication, and land use and land transformation; damages to resources are expressed as surplus energy for the future mining of resources.

The output of the LCA analysis will therefore be the *ecopoints* associated with each product, which will be subsequently used for DEA efficiency analysis. The *ecopoints* method was developed in Switzerland in 1990 and is based on the use of national government policy objectives [1]. Environmental impacts are assessed directly and emissions are weighted in relation to environmental quality targets. That is to say, the evaluation principle used is the distance to target principle, or the difference between the total impact in a specific area and the target value (these results are calculated in dimensionless *ecopoints*). It should be stressed that various political, economic, and social considerations also play a role when formulating these objectives. In fact, the *ecopoints* method is not so much an absolute environmental indicator as an indicator "in conformity with policy" and has been widely accepted as a useful instrument, although it is clear that several objections can be raised against the use of politically established target levels [6].

In accordance with the above data, the results considering the impact categories of the Eco-Indicator 99 are presented in Table 2. Although the values of the environmental impacts per unit of product will be used for the DEA model presented in the next section, the corresponding per ton impact values are also of interest and are, thus, also shown in Table 2. Note that the environmental impact ranking of the products is rather different in both cases, with the cell phone having the smallest unit impact but the highest impact considering its small weight. This does not mean that products with high unit impact values (e.g., fridge) necessarily have a low impact per ton. This depends clearly on the product weight. Table 3 shows the percentage of the total score per product calculated in Table 2 associated with the environmental impact of each component.

Table 2 Environmental impact of considered products (ecopoints)

Product	Human health	Ecosystem quality	Resources	Total
	Environmental impact (per unit)			
Washing machine	1.74	0.69	3.52	5.95
Fridge	2.73	0.75	5.54	9.02
TV set	0.54	0.41	2.04	3.00
Cell phone	0.016	0.010	0.042	0.067
Computer	1.5	0.846	4.91	7.26
Coffee machine	0.3	0.0657	0.715	1.08
Vacuum cleaner	0.535	0.14	1.79	2.47
Hair dryer	0.0463	0.0129	0.21	0.27
Iron	0.188	0.0405	0.369	0.60
	Environmental impact (per ton)			
Washing machine	28.76	11.40	58.18	98.35
Fridge	68.25	18.75	138.50	225.50
TV set	34.62	26.28	130.77	192.31
Cell phone	140.35	87.72	368.42	587.72
Computer	65.22	36.78	213.48	315.65
Coffee machine	100.00	21.90	238.33	360.00
Vacuum cleaner	118.89	31.11	397.78	548.89
Hair Dryer	85.74	23.89	388.89	500.00
Iron	163.48	35.22	320.87	521.74

3 Eco-Efficiency Assessment

The proposed approach to assess the relative eco-efficiency of the nine EEE products analyzed in this study is based on DEA. This methodology has been extensively used to analyze different types of products such as printers [7], cars [24], software [14], etc., as well as to assess the environmental performance of power plants [12, 19], dairy farms [28], paper mills [3, 11], countries [38, 39], etc. Kuosmanen and Kortelainen [20] use a simple DEA model to compute the eco-efficiency of road transportation in some large towns in Finland. Kuosmanen and Kortelainen [21] use a different DEA model to compute the eco-efficiency of sport utility vehicles. The proposed DEA approach is different in several respects:

- It is not just different models of a same product type that are compared, but a variety of different electric and electronic products.

Table 3 Percentage of the total ecopoints score of each product corresponding to each of its components

Components	Washing machine (5.95 Pt; %)	Fridge (9.02 Pt; %)	TV set (3.00 Pt; %)	Cell phone (0.067 Pt; %)	Computer (7.26 Pt; %)	Coffee machine (1.08 Pt; %)	Vacuum Cleaner (2.47 Pt; %)	Hair dryer (0.27 Pt; %)	Iron (0.60 Pt; %)
ABS					9.34		3.71	37.53	19.77
Aluminium	15.41	16.63	4.03	2.57	3.37	42.13	24.96	11.36	63.48
Bronze					1.96				
Cardboard					0.03				
Concrete	5.58								
Copper		6.05	26.87	37.74	33.66	15.93	47.15	44.61	11.49
Epoxy resin				11.28					
Glass		0.43	29.49	1.75	3.02	2.81			0.01
Iron	36.81	36.7	7.4	0.88	13.57			3.83	
Lead				0.63	0.54				
Magnesium				2.85					
Nickel				11.84	6.43				
Oil and CFC		1.2							
Other Materials			22.06						
Paper							0.04		
Phosphorus			0.45						
Plastic	22.54	11.87	9.7						
Polypropylene					12.37	34.8	9.19	0.98	
Polycarbonates					6.14				
Polystyrene				13.45			5.37		
Polyurethane		23.62							
PVC				3.02	2.65	2.75	4.07		
Rubber					0.13		1.32		0.53
Silicon				3.76	1.1				
Steel (stainless)	19.66					1.58	3.44	1.69	4.72
Textile							0.75		
Tin plate				0.29	0.38				
Water with R11		3.11							
Wood	0.00								
Zinc				9.94	5.31				

- Conventional LCA impact scores are used, thus, measuring all environmental effects throughout the whole life cycle and not only those of the production phase.
- Retail price information is used.

We thus use a standard DEA model, the inputs and outputs considered in the DEA approach as well as the heterogeneity of the products that are assessed constituting the novelty of our study.

In this study, retail price (shown in Table 4) is the only output considered. Environmental impacts are considered as inputs.

As there are large differences in sizes, weights, and prices among the products we are comparing, variable returns to scale (VRS) were assumed. An input orientation and an additive metric are adopted. The eco-efficiency score can therefore be interpreted as the sum of the possible reductions (in ecopoints) across the environmental impact categories considered. Thus, a zero score means that the corresponding product is eco-efficient relative to the other products, whereas a positive score for a product means that given its economic value, smaller environmental impacts should be expected.

Table 4 Average retail prices for the analyzed appliances

Product	Price
Washing machine	522€
Fridge	780€
TV set	155€
Cell phone	**77€**
Computer	1,100€
Coffee machine	29€
Vacuum cleaner	500€
Hair dryer	20€
Iron	25€

To mathematically formulate the model, let us call:

N	Number of products
C	Number of impact categories
i=1,2,…, C	Index on impact categories
j=1,2,…, N	Index on products
I_{ij}	Impact value of product j on environmental category i
P_j	Retail price of product j
$(\lambda_1, \lambda_2 \ldots, \lambda_N)$	Vector of auxiliary non-negative variables
α_i	Attainable reduction in impact category i
γ_J	Eco-efficiency score of product J

Note that the lambda variables above represent the coefficients in a linear combination of the products data. This linear combination is used to define a target lying on the efficient frontier and against which the product is benchmarked. The DEA model used to assess the eco-efficiency of a product J considers environmental impacts as inputs and prices as output. It can be formulated as:

Maximize

$$\gamma_J = \sum_{i=1}^{C} \alpha_i$$

s.t.

$$\sum_{j=1}^{N} I_{ij} \cdot \lambda_j = I_{iJ} - \alpha_i \quad i = 1, 2, ..., C$$

$$\sum_{j=1}^{N} P_{ij} \cdot \lambda_j \geq P_J$$

$$\sum_{j=1}^{N} \lambda_j = 1$$

$$\lambda_j \geq 0 \quad j = 1, 2, \ldots, N \quad \alpha_i \geq 0 \quad i = 1, 2, \ldots, C$$

This is a simple LP model with NC variables and $C2$ constraints. The constraints guarantee that the computed solution has lower impact values with no lower price. The convexity constraint on lambda variables imposes the VRS assumption. The objective function γ_J represents the sum of the reductions in the different environmental impact categories. Note that although the above model assumes all impact categories to be equally important, as in other DEA models (e.g., Kuosmanen and Kortelainen [20]), it is easy to include weight factors to incorporate any information on the relative importance of different environmental impacts.

4 Eco-Efficiency Results

As mentioned above, DEA not only provides an efficiency score but also target environmental impact levels against which the performance of any environmental improvement program may be benchmarked. Table 5 shows the eco-efficiency scores, estimated environmental impact reductions, and resulting goals for the nine EEE products under study. The appliances selected are common household representatives of the electric and electronic equipment category, a category whose economic relevance is undeniable. The proposed methodology, however, is contingent neither on the category nor on the specific products selected but can be applied to any other chosen category or products. The DEA software used was the efficiency measurement system freely available on the Internet [29].

On the one hand, the column labeled "decrease" (Table 5) represents the reduction in ecopoints in that impact category (variables α_i in the DEA model) that would be necessary for the product to be eco-efficient for each of the three environmental impact categories. On the other hand, the column labeled "goal" represents the resulting impact value taking into account the mentioned reduction. The last column shows the eco-efficiency score γ_J and corresponds to the sum of the "decrease" columns of the three impact

Table 5 Eco-efficiency scores, impact reductions, and targets

	Human health		Ecosystem quality		Resources		Eco-Efficiency
Product	Decrease	Goal	Decrease	Goal	Decrease	Goal	
Washing machine	1.170	0.570	0.524	0.166	1.616	1.904	3.309
Fridge	1.745	0.985	0.281	0.470	2.294	3.246	4.319
TV set	0.428	0.112	0.376	0.034	1.676	0.364	2.480
Cell phone	0.000	0.016	0.000	0.010	0.000	0.042	0.000
Computer	0.000	1.500	0.000	0.846	0.000	4.910	0.000
Coffee machine	0.284	0.016	0.056	0.010	0.673	0.042	1.013
Vacuum cleaner	0.000	0.535	0.000	0.140	0.000	1.790	0.000
Hair dryer	0.030	0.016	0.003	0.010	0.168	0.042	0.201
Iron	0.172	0.016	0.031	0.010	0.327	0.042	0.530

categories. Note that only three of the products are eco-efficient: namely, the cell phone, desktop computer, and vacuum cleaner. Corresponding reductions in environmental impact are estimated for the other products. The objective function of the DEA model maximizes the sum of the reductions on the three categories of environmental impact. These reductions are measured in absolute terms, i.e., in ecopoints. Relative reductions, however, correspond to the amounts that these reductions imply measured as a percentage w.r.t. the current impact values. Table 6 shows the "goal" impact values as a percentage of current impact values. In absolute terms, the least eco-efficient products of the sample are bulky products such as the fridge, washing machine, and TV set. Note, however, that except for the TV set, the total environmental impact reductions of these products is smaller, in relative terms, than for the rest of the products.

Finally, Table 7 shows the peer group and the local returns to scale of the different products. Mathematically, the peer group is formed by the products that intervene with a non-zero coefficient in the convex linear combination that gives the optimal solution to the DEA model. Only eco-efficient products can be in the peer group of the product being evaluated, and these peer products that jointly define the goal for the product being assessed are considered as benchmarks, i.e., reference products that are eco-efficient and whose cases should be studied by the product under assessment in an attempt to learn the necessary lessons so as to increase its level of eco-efficiency. Note that of the three eco-efficient products, the cell phone is the one that appears most often as a benchmark. Furthermore, this product is the only one that locally exhibits constant returns to scale and is therefore scale efficient, i.e., it has the most productive scale size [2]. The other two eco-efficient products (i.e., the computer and vacuum cleaner) exhibit decreasing returns to scale, i.e., although they are technically efficient, the scale of their inputs and output is not optimal.

Of the eco-inefficient products, as expected, large ones (such as the washing machine, fridge, and TV set) exhibit decreasing returns to scale, whereas small ones (such as the coffee machine, hair dryer, and iron) exhibit increasing returns to scale. This information on local returns to scale is only indicative. Thus, for those that exhibit decreasing returns to scale, the information is that the scale at which environmental impacts (i.e., ecopoints) are "transformed" into value (i.e., euros) is not optimal, but larger than the optimal scale, and thus, scale efficiency (and global efficiency) would increase if both their price and environmental impacts were lower. This means that from an eco-efficiency perspective, redesign of the product with perhaps less functionality and complexity and a lower value, but with less environmental impact, may be more desirable. For products exhibiting increasing returns to scale, however, scale efficiency (and global efficiency) would increase if both their price and environmental impacts were higher. This means that from an eco-efficiency perspective, redesign of the product with more functionality and utility and a higher value even with more environmental impacts is probably more desirable.

Table 6 Environmental impact targets as a percentage of present impact values

Product	Human health (%)	Ecosystem quality (%)	Resources (%)	Total (%)
Washing machine	32.8	24.0	54.1	44.4
Fridge	36.1	62.6	58.6	52.1
TV set	20.7	8.3	17.9	17.1
Cell phone	100.0	100.0	100.0	100.0
Computer	100.0	100.0	100.0	100.0
Coffee Machine	5.3	15.2	5.9	6.3
Vacuum cleaner	100.0	100.0	100.0	100.0
Hair dryer	34.6	77.5	20.0	25.3
Iron	8.5	24.7	11.4	11.4

Table 7 Peer group and returns to scale

Product	Peer group	Returns to scale
Washing machine	Vacuum cleaner and computer	Decreasing
Fridge	Vacuum cleaner and computer	Decreasing
TV set	Cell phone and vacuum cleaner	Decreasing
Cell phone	–	Constant
Computer	–	Decreasing
Coffee machine	Cell phone	Increasing
Vacuum cleaner	–	Decreasing
Hair dryer	Cell phone	Increasing
Iron	Cell phone	Increasing

The relation of the eco-efficiency results with the concept of product dematerialization, i.e., reducing the volume of materials in a product without affecting its functionality, is worth noting. For two of the three eco-efficiency products (cell phone and computer), the reduction in size, weight, and energy consumption has been substantial. For these products, most of their value is not embedded in the physical product, i.e., the hardware, but in their extended-product features, i.e., software and services. Actually, the trend is common for all the tested products and cannot but grow in the future: cleverly design lighter products, increase their embedded intelligence, and use this to leverage their value to the customer. This recipe, no doubt, contributes to increasing their eco-efficiency.

5 Conclusions

In this paper, a DEA approach has been used to compute the relative eco-efficiency of a diverse sample of commonplace household EEE products, presenting very different characteristics as regards technologies, weights, etc.

The approach involves solving a simple LP model using the average retail price of the products and their environmental impact values computed using LCA as data. The results show that of the nine products considered only three, namely the computer, vacuum cleaner, and cell phone, are technically eco-efficient and that only one, namely the cell phone, is eco-efficient in overall terms. For the other products, significant reductions in environmental impact are determined and an overall eco-efficiency score is computed. DEA also provides useful information on product benchmarks and local returns to scale.

The results of the analysis can help consumers to assess and become aware of the eco-efficiency of the products they use. The proposed approach also provides information to designers and manufacturers as regards the relative eco-efficiency levels of their products, target impact values, benchmark products for improving eco-efficiency, etc. Finally, although the sample used in this study is small and belongs to a specific category, the proposed methodology is contingent neither on the product category nor on the specific products selected, but can be applied to any other chosen category or products.

As for possible future lines of research, we are currently working on adapting the DEA approach to include the lifespan of a product in the calculations of its eco-efficiency. Thus, from this point of view, cell phones, which are disposed of after a relatively short period of time would be penalized even if their components were recycled.

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