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Environmental Effects of Consumption: An Approach Using DEA and Cost Sharing

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Summary

In this paper we propose an approach to evaluation of the environmental effects of consumption goods. The approach consists of two steps, namely (1) an assignment of environmental effects of different types to the consumption activities, followed by (2) a comparison of the consumption activities with respect to their environmental impacts as found in the first step.

For the assignment of environmental effects to activities we propose to use the method of cost allocation, applied to a multiple of different environmental impacts considered as different "costs". This leads to a consideration of vector cost allocation and its relation to ordinary one-dimensional cost allocation methods; in particular, we consider the stability of cost sharing rules under composition of cost functions, a property which is important in the application at hand. For part (2) of the approach we exploit the well-established methodology of DEA (Data Envelopment Analysis) in order to aggregate vectors of environmental effects to a single index of relative environmental impact of a consumption activity.

An application of the last part of the approach is given, based on Danish national accounts data and using emission data as a proxy for environmental effect.

Keywords: Consumption activities, environmental effects, cost sharing, data envelopment analysis

JEL: D24, C71, Q25

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ENVIRONMENTAL EFFECTS OF CONSUMPTION: AN APPROACH USING DEA AND COST SHARING

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Abstract:

In this paper we propose an approach to evaluation of the environmental effects of consumption goods. The approach consists of two steps, namely (1) an assignment of environmental effects of different types to the consumption activities, followed by (2) a comparison of the consumption activities with respect to their environmental impacts as found in the first step.

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1. Introduction

The central importance of environmental problems even for the conduct of the everyday economic activities has long been realized and it has given rise to environmental policies which influence almost every aspect of life. Nevertheless, there is a need for continued attention to problems of environment, not only on the part of policy makers but also for the general public. An awareness of the environmental effects of ordinary day-to-day activities may be enhanced by the systematical collection and publishing of data on environmental impacts of activities in the economy; since consumption is usually taken as the end goal of economic activity, environmental effects of consumption would illustrate the impacts in a useful way.

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In the economic models of production and exchange, consumption is implicitly taken as the ultimate goal of all economic activity – allocations are compared according to the utility they give the consumers – and it seems therefore reasonable that consumption activities are the ultimate causes of pollution and environmental decay. However, consumption as such is usually not causing any damage to the environment; what pollutes are the production activities that were carried through in order to make the consumption possible. This means that an attemt to disclose the impact on the environment of different consumption activities we face the task of assigning an environmental impact, which has arisen elsewhere in the economy, to the different consumption activities, in principle down to consumption of each single commodity.

From a formal point of view, what we have here is a cost allocation problem (as considered e.g. by Young, 1994), however with the additional feature that the "cost" to be allocated (to consumption activities) is not a monetary cost but rather a vector of changes in environmental state, measured in the relevant indicators. Although a vector cost allocation problem is not qualitatively different from a standard cost allocation problem, some new features do arise, and since they have some relevance to the problem at hand, we shall consider them at some length in the text.

First of all, in the context of vector cost allocation it makes sense to consider compositions of cost functions; in the case of environmental impact one may consider the emissions (of relevant polluting gases) as a (multi-dimensional) "cost" of consumption, whereas the final effect on the environment caused by the emissions may be considered as another vector cost function; their composition, then, gives us the effect of consumption on environment. In such a situation, where the composition of cost functions is a natural feature, it seems reasonable that the cost allocation rule should respect such compositions, at least for sufficiently well-behaved cost functions. It turns out that this composition compatibility is a crucial property of abstract cost allocation, since it entails other, more well-known properties of one-dimensional cost allocation rules such as additivity, and conversely is implied by this.

While the composition property takes us into the realm of additive cost allocation rules satisfying the dummy property, there are still many possible choices (as explained e.g. in the recent work by Friedman and Moulin, 1999). However, the additional features of our application will narrow down the choice considerably. Indeed, since our ultimate task is that of assigning environmental impact to consumption, the allocation rule should satisfy the monotonicity property that if the some particular consumption activity increases then its share in the environmental cost should not decrease. Taking this property into consideration (together with a strong form of composition compatibility adapted to our situation), we can single our choice of allocation rule down to the family of random order allocation methods.

For the final stage, that of aggregating the different environmental costs of a given consumption activity into a single number or index of environmental impact, we rely on the DEA methodology (cf. Charnes, Cooper and Rhodes, 1978), which avoids the introduction of arbitrary weights for the evaluation of different aspects of the environment. In most applications of the DEA methodology, including those related to environmental efficiency, cf. e.g. Taskin and Zaim (2001), the comparisons are carried out between units for which it is at least in principle conceivable that they have access to the same underlying technology for producing outputs (good or bad) from inputs. In the application which we have in mind, namely the comparison of environmental effects of different consumption activities, this is no longer obviously the case. On the other hand, taking the market value of aggregate consumption of a given type as an indication of its importance to the consumers, measuring environmental effect per unit of market value may give an indication of the extent to which the particular consumption activity has detrimental side effects. Therefore, our approach amounts to visualizing consumption as production of consumer satisfaction; the different consumption activities are individual technologies for producing satisfaction, and outcome is measured in money terms; the environmental "bads" which are by-products of this production of consumer satisfaction may be treated as inputs in the aggregate consumption technology; the smaller their value, the better.

The paper is organized as follows: In Section 2 below, we introduce the background model as a frame of reference for the subsequent discussion; this is a model of an economy where production and consumption give rise to externalities in the form of a change in certain variables describing the state of the environment. The problem to be considered is then to devise a system of accounting such that the change in environmental state is ascribed to the consumption activities in a suitable way. This problem, which is one of multidimensional cost allocation, is considered in generality in Section 3. Adding in Section 4 certain features of the main application to the model, particularly the lack of reliable data on final environmental impacts leading their replacement by emission data, we are led to a particular method of cost allocation, namely the so-called random order method. In Section 5 we describe the subsequent aggregation phase, where DEA is used to give an index of relative environmental impact. An example of such a computation using DEA on emission data for the Danish economy is given in Section 6, and finally Section 7 contains some concluding comments on the method and its future extensions.

2. A general model of external effects and the problem of assigning external effect to individual commodities

In the present section, which serves as a general background for the following sections, we introduce a formalized version of an economy with external effects (pollution) caused by the level of economic activity. In order to assign an environmental impact to a particular activity (in our model, to the consumption goods), two problems must be faced, namely (1) the allocation of each type of environmental effect on activities, and (2) aggregation of vectors of environmental effects to numbers or indices. These problems are then considered in the following sections.

We consider a society which engages in activities of production and consumption of commodities; the main point of our study is of course the environment effects of these activies, so that our basic model is one of an *economy with externalities;* to keep the model reasonably simple, we confine our attention to production externalities.

The economy is defined as follows: There is a set $L = \{1, \dots, l\}$ of commodities and a set $S = \{1, \dots, s\}$ of (undesirable) environmental effects; these effects are caused by the production activites and in their turn influences both production and consumption. We interpret the environmental effects literally as *deterioration of the environment* (reduction in the ozone layer, deterioration of water quality etc.); indeed, the distinction between environmental effects and *emissions* of polluting material is what creates the need for a “cost allocation” approach.

It should be noticed at this point that for a more detailed analysis of an economy with externalities of the type considered here, we would need to distinguish between the state of the environment (as measured by the s indicators introduced above) at the beginning of each period, which would enter into the description of the production capabilities and utility functions in this period, and the state at the end of the period, changed by the activities carried out in the period. Since we have the more modest aim of devising a method for assigning environmental changes to consumption activities (rather than analysing the impact of the choices of the agents on the future path of the environmental indicators), our present atemporal approach will suffice.

The characteristics of the economy are introduced in the following way: There are m consumers, consumer i being described as (X_i, u_i, ω_i), where for each i,

- $X_i \subset \mathbb{R}^{L \times S}$ is a set of feasible consumption plans (given the environmental impact ξ_i),
- $u_i : X_i \to \mathbb{R}$ a utility function on X_i, and
- $\omega_i \in \mathbb{R}^L$ an initial endowment,

and where for each j, $Y_j \subset \mathbb{R}^L \times \mathbb{R}^{L \times S}$ is a production set, whereby a production plan $(y_j, \eta_j; \xi_j)$ is interpreted as the net production of commodity bundle y_j with an associated environmental effect of η_j, given that the overall environmental change is ξ_j). Thus, production gives rise to externalities whereas consumption does not; however, consumption externalities may easily be introduced into the model.

An allocation z is a collection of consumption bundles $(x_i; \xi_i) \in X_i$ for $i = 1, \dots, m$ and of production plans $(y_j, \eta_j; \xi_j) \in Y_j$ which is aggregate feasible in the sense that

$$\sum_{i=1}^{m} x_{ih} \leq \sum_{j=1}^{n} y_{jh} + \sum_{i=1}^{m} \omega_{ih}, \ h \in L,$$

$$\xi_i = \xi_{i'} = \xi_j, \ i, i' \in \{1, \dots, m\}, \ j \in \{1, \dots, n\}, \ \sum_{j=1}^{n} \eta_j = \xi_j.$$

Thus, environmental effects are in the context of this models considered as a public good (or rather as a public “bad”) which takes the same value for all agents, but which in its turn is built up by the individual polluting effects of the producers.

As is well-known, the presence of externalities in the economy will prevent the market from working in a satisfactory way; indeed, the equilibria are not Pareto optimal, and there is a need for regulation; however, for a regulation to be successful, one needs to evaluate the preferences of society with respect to (reduction of) environmental impact, or at least to measure this impact in a way which takes these preferences into consideration, and this is the main goal of the paper. In the context of the present model, what is aimed at is an assignment of the S-dimensional vector of environmental impacts to the consumption of each commodity, that is a function which to every allocation z with associated vector of environmental effects ξ gives an L-tuple of S-vectors $(\hat{\xi}_{hk})_{h\in L,k\in S}$ such that

$$\sum_{h\in L}\hat{\xi}_{hk}=\xi_k \text{ each } k\in S.$$

At present, we shall confine ourselves to the search for a cost assignment method which satisfies some basic requirements. In the longer perspective, not to be touched upon at present, the assignment of environmental impacts to consumption goods might hopefully be carried out in such a way that it could be of use in decentralized decision making.

3. Sharing a vector-valued cost

Following up on what was said above, in the present section we consider methods for allocating environmental impact of a given type to consumption of each commodity. The intuition behind such an allocation of environmental impact to each consumption activity, whereby the consumption as such may not give rise to any external affects although production does, or conversely, is that consumption is the ultimate activity responsible for the pollution which it has given rise to even in an indirect way.

Thus, we consider a situation where there is a given functional relationship $C:\mathbb{R}^L_+\to\mathbb{R}^S$ which to each level of (consumption) activities $x=(x_1,\dots,x_l)$ assigns a vector $C(x)$, which may be interpreted as a vector-valued cost, or an environmental effect measured as several physical quantities. We are looking for a *sharing rule* which to each x_i assigns an S-dimensional vector interpreted as the *shares* (in environmental damage of each type) of the ith consumption activity. Thus, the sharing rule should distribute the total environmental impact among the different consumption activities which are considered as the ultimate causes of the pollution.

Since environmental effects are multiple, this is not a standard cost-sharing problem; it is however quite closely related to the cost allocation problem as treated extensively in the literature (Moulin and Shenker, 1992; Young, 1994; Sprumont, 1998; Friedman and Moulin, 1999). Below we introduce the vector valued cost allocation problem in some detail and describe its connection with the standard cost allocation problem.

In the following, a vector cost function is a nondecreasing map $C:\mathbb{R}^n_+\to\mathbb{R}^d_+$. A d-dimensional *vector cost allocation rule* is a map, which to each vector cost function $C:\mathbb{R}^n_+\to\mathbb{R}^d_+$ and each (input) array $q=(q_1,\dots,q_n)$ assigns numbers $x_{ij}(q;C)$, $i=1,\dots,n$, $j=1,\dots,d$, such that

$$\sum_{i=1}^{n}x_{ij}(q;C)=C_j(q).$$

We write the vector cost allocation rule as $x^{(\cdot)}$. A vector cost allocation rule is *additive* if

$$x_{ij}(q,C^1+C^2)=x_{ij}(q;C^1)+x_{ij}(q;C^2)$$

for arbitrary functions $C^1, C^2 : \mathbb{R}^n_+ \to \mathbb{R}^d_+$. Under the assumption of additivity, we may write $C = C_1 + \cdots + C_n$, where C_i is the function whose ith coordinate is identical with that of C and with 0 in all other coordinates, and consequently the cost allocation rule splits into d one-dimensional (that is, ordinary) cost allocation rules. Thus, under additivity there is nothing new to be obtained from considering vector cost allocation problems, since they are only a collection of the usual cost allocation rules. This is actually not too surprising, since our working with vector cost functions of the type described above presupposes that the d different "costs" (or, as in our case, environmental damage effects) are produced in exact amounts from the inputs. We shall see later how the problem can be further generalized to the case of qualitatively new features.

In the context of vector cost functions, it makes sense to consider compositions of cost functions. Let $C : \mathbb{R}^n_+ \to \mathbb{R}^m_+$, $D : \mathbb{R}^m_+ \to \mathbb{R}^d_+$ be vector cost functions. We say that $x^{(\cdot)}$ is consistent under left composition with vector cost functions in the class $\mathcal{C}$ if

$$x^{(d)}_{ij}(q; D \circ C) = \sum_{k=1}^{m} x^{(m)}_{ik}(q; C) \frac{x^{(d)}_{kj}(C(q); D)}{C_k(q)} \text{ for all } i, j, \tag{1}$$

holds for all C, when D is chosen from the class $\mathcal{C}$, and similarly, that $x^{(\cdot)}$ is consistent under right composition with vector cost functions in the class $\mathcal{C}$ if (1) holds for arbitrary D and C is taken from $\mathcal{C}$. Finally, $x^{(\cdot)}$ is consistent under composition with cost functions in $\mathcal{C}$ if it is consistent under both left and right composition with functions in $\mathcal{C}$.

Thus, if a cost allocation rule satisfies composition consistency, then allocating directly from final costs to initial inputs or allocating final costs to intermediate costs which are then attributed to initial inputs will yield the same result. In our main result below, the class $\mathcal{C}$ is taken to be the class $\mathcal{L}$ of (positive) linear mappings.

The summation in (1) gives some indication of a connection between our notion of composition consistency and the usual axiom of additivity of one-dimensional cost allocation rules. However, an additional property of the vector cost allocation rule is needed in order to establish the connection: We say that the vector cost allocation rule *reflects direct cost* if

$$x^{(1)}_i(q; +) = q_i,\ i = 1, \dots, n, \text{ for each } q = (q_1, \dots, q_n) \in \mathbb{R}^n_+,$$

where $+$ is the "cost" function taking $(q_1, \dots, q_n)$ to $\sum_{i=1}^n q_i$. The terminology is taken from cost accounting; indeed, if the aggregate cost of an array of goods is entirely composed of direct cost, so that aggregate cost is a sum of individual direct costs, then any meaningful cost allocation rule should indeed reflect this in the sense that the cost allocated to good i is its direct costs, no more no less.

Finally, we need a rule for treating cost allocation when we concatenate two independent cost allocation problems to one: We say that $x^{(\cdot)}$ satisfies *independence* if for any two cost functions $C^r : \mathbb{R}^{N_r}_+ \to \mathbb{R}^{D_r}_+$, $N_r = \{1, \dots, n_r\}$, $D_r = \{1, \dots, d_r\}$ $r = 1, 2$, we have that

$$x^{(d_1+d_2)}_{ij}((q^1, q^2); (C^1, C^2)) = \begin{cases} x^{(d_r)}_{ij}(q^r; C^r) & \text{if } i \in N_r,\ j \in D_r, \\ 0 & \text{otherwise} \end{cases}$$

Thus, if independence holds, then the allocation in a given problem is not affected by the fact that another cost allocation problem is considered simultaneously, as long as neither the inputs nor the costs are in any way related. As it can be seen, this property implies the well-known dummy property for one-dimensional cost sharing (stating that if a cost function does not depend on some variable q_i, then the share of this variable is 0).

We now have the following result:

THEOREM 1. *Assume that $x^{(\cdot)}$ is a vector cost allocation rule which is consistent under left composition with cost functions in $\mathcal{L}$, satisfies independence and reflects direct cost. Then the one-dimensional rule $x^{(1)}$ satisfies additivity and the dummy rule. Conversely, every additive one-dimensional cost allocation rule can be extended to a vector cost allocation rule which is consistent under left composition with maps in $\mathcal{L}$, satisfies independence and reflects direct cost.*

PROOF: Let $C^1 : \mathbb{R}^n_+ \to \mathbb{R}_+$ and $C^2 : \mathbb{R}^n_+ \to \mathbb{R}_+$ be two cost functions, and consider the composition (to the left) of the vector cost function $C = (C^1, C^2) : \mathbb{R}^n_+ \to \mathbb{R}^2_+$ with the (linear) cost function $+ : \mathbb{R}^2_+ \to \mathbb{R}_+$. Applying (1) we get that

$$x_i^{(1)}(q; C^1 + C^2) = x_i^{(1)}(q; + \circ (C^1, C^2)) = \sum_{k=1}^{2} x_i^{(1)}(q; C^k) \frac{x_k^{(1)}(C(q); +)}{C^k(q)} \tag{2}$$

for each i. Since $x^{(\cdot)}$ reflects direct cost, the fractions in (2) are equal to 1, and we get that

$$x_i^{(1)}(q; C^1 + C^2) = x_i^{(1)}(q, ; C^1) + x_i^{(1)}(q, ; C^2), \text{ each } i,$$

so that $x_i^{(1)}$ is indeed an additive allocation rule.

Next, if $C : \mathbb{R}^n_+ \to \mathbb{R}_+$ is a (one-dimensional) cost function which does not depend on the ith coordinate, then $C = + \circ (C_{-i}, 0)$, where $C_{-i} : \mathbb{R}^{n-1}_+ \to \mathbb{R}_+$ is defined by

$$C_{-1}(q_1, \dots, q_{i-1}, q_{i+1}, \dots, q_n) = C(q_1, \dots, q_{i-1}, 0, q_{i+1}, \dots, q_n).$$

By independence, we have that $x_{i1}^{(2)}((q_{-i}, q_i); (C_{-i}, 0)) = 0$ and

$$x_{i2}^{(2)}((q_{-i}, q_i); (C_{-i}, 0) = x_i^{(1)}(q_i; 0) = 0,$$

where the last equality follows from the definition of a cost allocation rule. Thus we have that $x^{(1)}$ has the dummy property.

Conversely, assume that x is a (one-dimensional) cost allocation rule which is additive. Define the vector cost allocation rule $x^{(\cdot)}$ by $x^{(1)} = x$ and

$$x_{ij}^{(m)}(q; C) = x_i(q; C_j), \ i = 1, \dots, n, \ j = 1, \dots, d,$$

for any vector cost function $C : \mathbb{R}^n_+ \to \mathbb{R}^d_+$. It follows directly from the construction that $x^{(\cdot)}$ satisfies the independence property. We check that $x^{(\cdot)}$ reflects direct cost and satisfies composition consistency.

For the first of these properties, let $+$ be addition of n "cost" components, $+(q_1,\dots,q_n)=\sum_{i=1}^n q_i$. Then

$$+(q_1,\dots,q_n)=\sum_{i=1}^n \mathrm{pr}_i(q_1,\dots,q_n),$$

where $\mathrm{pr}_i:\mathbb{R}_+^n\to\mathbb{R}_+$ is projection on the ith factor, so that

$$x_i^{(1)}(q;+)=x_i^{(i)}(q;\sum_{j=1}^n \mathrm{pr}_j)=\sum_{j=1}^k x_i^{(1)}(q;\mathrm{pr}_j)=q_i,$$

where we have used additivity together with the fact that

$$x_i^{(1)}(q;\mathrm{pr}_j)=\begin{cases} q_i & \text{if } i=j,\\ 0 & \text{otherwise}\end{cases}$$

by the dummy axiom. We conclude that $x^{(\cdot)}$ reflects direct cost.

Finally, let $C:\mathbb{R}_+^n\to\mathbb{R}_+^m$, $D:\mathbb{R}_+^m\to\mathbb{R}_+^d$ be maps with $D\in\mathcal{L}$, and consider the composed map $D\circ C$. By independence, it suffices to treat the case $d=1$. Since D belongs $\mathcal{D}$, we have that $D(q_1',\dots,q_m')=\sum_{j=1}^m b_j q_j'$ for some fixed $b_j\geq 0$, $j=1,\dots,m$, so that

$$D\circ C(q_1,\dots,q_m)=\sum_{j=1}^m b_j C_j(q_1,\dots,q_n).$$

Using additivity, we therefore get that

$$x_i^{(1)}(q;D\circ C)=\sum_{j=1}^m b_j x_j^{(m)}(q;C)=\sum_{j=1}^m b_j x_j^{(m)}(q;C),$$

and since trivially $b_j=x_j^{(1)}(q;D)/D_j(q)$, we have consistency under left composition with maps in $\mathcal{L}$. ☐

The theorem shows us that the intuitively reasonable properties of consistency under left linear transformation, independence, and reflection of direct costs reduce the vector cost problem to the case of several cost allocation problems of the type usually considered (satisfying additivity and dummy, cf. Friedman and Moulin, 1987). However, the broader context of vector cost allocation may be useful, not only in the context of genuinely vector-valued cost, but also for deriving results in the simpler world of one-dimensional cost allocation.

4. Environmental impact of consumption

Having considered in the previous section general methods for allocating vector valued cost among commodities or activities giving rise to this cost, we return now to our main case, that of constructing a measure of the environmental impact of consumption. As mentioned previously, environmental impact should be considered as the deterioration (of different types) of environmental conditions caused by the economic activities. However, these changes in the state of the environment are usually measured only in a partial and incomplete way; what is measured is the level of *emission* of various kind. Indeed, the environmental impact of the economy in terms of emissions is already calculated in certain countries. In this calculations, which make use of the input-output tables for the national economy, emissions are assumed to be linear functions of activity.

Unfortunately, the connections between emissions and environmental changes are not very well documented, and they are presumably non-linear. Though desirable, it is as yet beyond reach to allocate environmental effects directly to consumption activities; instead, effort might be directed towards an allocation of environmental effects to emissions, which might then be followed up by allocating further back from emissions to consumption activities. There is a point in this two-step procedure – the assignment of environmental effects to emissions depends only on physics and is the same for every country, whereas the second step takes its origin in the national input-output relationships and as such must be country-specific.

For this two-step procedure to be viable, the cost allocation rule should be consistent with right composition with linear maps (assuming emission to be subject to constant returns to scale), which is seen to be a further restriction as compared with those considered in the previous section. The following lemma is straightforward.

LEMMA 2. *Let $x^{(\cdot)}$ be a vector cost allocation rule which is consistent with compositions in $\mathcal{L}$, satisfies independence, and reflects direct cost. Then each $x_{\cdot j}^{(m)}$ satisfies scale invariance in the sense that*

$$x_{\cdot j}^{(m)}((\lambda q_i, q_{-i}); C_{i,\lambda}) = x_{\cdot j}^{(m)}(q; C)$$

for each $i \in \{1, \ldots, n\}$ and $\lambda > 0$, where $C_{i,\lambda}$ is the rescaled cost function defined by $C_{i,\lambda}(q) = C(\lambda^{-1} q_i, q_{-i})$.

PROOF: Since the map $\tau_{i,\lambda}$ given by $\tau_{i,\lambda}(q_i, q_{-i}) = (\lambda q_i, q_{-i})$ is linear and $C = C_{i,\lambda} \circ \tau_{i,\lambda}$, we have the result of the lemma. □

In view of Lemma 2, the components of a vector cost allocation procedure to be used for determining environmental "cost" of consumption activities must satisfy scale invariance (in addition to the properties discussed in the previous section). This means that the components $x_{\cdot j}^{(m)}$ share some crucial properties of the so-called *random order* methods for cost allocation (cf. Friedman and Moulin (1999), pp. 293).

Actually, there is a further reason for choosing random order methods: Since data for environmental effects of emissions are as yet not sufficiently detailed for practical purposes, we shall have to concentrate on emissions for the numerical calculations. Since the problem of assessing environmental impact of consumption is anyway multidimensional and involves aggragation over emissions or environmental effects, it seems reasonable to demand that the cost allocation rule is *monotonic* (or respects dominance) in the sense that if $q \geq q'$ (in the application meaning that the emission vector q dominates the vector q', with the effect that the vector $C(q)$ of environmental effects dominates that of $C(q')$), then $x_{ij}^{(m)}(q;C) \geq x_{ij}^{(m)}(q';C)$ (the effects are allocated to each emissions in such a way that domination is retained).

The two conditions of scale invariance and monotonicity (together with a technical condition to be described) do indeed determine the method of cost allocation to be used.

THEOREM 2. *Let $x^{(\cdot)}$ be a vector cost allocation method which is consistent with composition with linear maps, satisfies independence, reflects direct cost, and further satisfies monotonicity and continuity at zero in the sense that lim$_{q_i \to 0}$ $x^{(m)}((q_i, q_{-i}); C) = x^{(m)}((0, q_{-i}); C)$ for each i. Then $x_{\cdot j}^{(m)}$ is a random order method for each j.*

PROOF: Direct consequence of Lemma 2 and Theorem 1 in Friedman and Moulin (1999). □

5. Aggregation of environmental indicators by DEA

In the context described above, the environmental effects of consumption activities may – at least in principle – be calculated, but so far in the form of vector cost assignments. If we want a one-dimensional measure of environmental impact of each consumption activity, we will have to aggregate over different effects, or rather, in view of the restrictions imposed by data, over different emissions.

The simplest way of aggregating environmental effects is by linear aggregation using fixed weights; this method has the additional advantage of being consistent with the cost allocation methods introduced above, since the linear aggregation amounts to a left composition of the vector cost function with a linear cost function. However, the choice of weights, which reflect the relative importance of the individual indicators, introduces a certain arbitrariness in the approach.

To avoid this arbitrariness, we propose to employ the techniques of Data Envelopment Analysis (cf. Charnes, Cooper and Rhodes, 1978). This means that we refrain from calculating an absolute index of environmental impact and replace this by an *index of relative environmental impact:* For each weight vector $w \in \mathbb{R}_+^L$ we may define the q-impact index of consumption activity h as the w-weighted effect per unit value of the activity. For each activity, we then choose the weight vector w which is the most favorable for this activity in comparison with the other activities; comparing the given commodity with the others in this way will give a relative impact index for the environmental impact of the given commodity.

The following result is well-known in the context of productivity analysis by DEA and adapted to our current purpose.

THEOREM 3. *Let ρ^h be the relative impact index of commodity h, let $\bar{a}$ be the column* *vector of environmental effects per unit value of consumption activity h, and let A be the matrix of effects per unit cost of the other consumption activities. Then ρ^h is the solution of the LP problem*

$$\min \rho$$

$$\text{such that}$$

$$\begin{pmatrix} \bar{a} & -A \\ 0 & (1,\ldots,1) \end{pmatrix} \begin{pmatrix} \rho \\ v \end{pmatrix} \geq \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}. \tag{2}$$

Proof: Let ρ^0 be the solution of (2). Then, by duality, the linear program

$$\min \mu$$

$$\text{such that}$$

$$(w_1,\ldots,w_L,\mu) \begin{pmatrix} \bar{a} & -A \\ 0 & (1,\ldots,1) \end{pmatrix} \geq (1,0,\ldots,0)$$

has an optimal solution, and its value equals ρ^0. From the matrix inequalities we have that

$$\sum_{k=1}^{L} w_k \frac{\partial C_k}{\partial q_j} \leq \rho^0$$

for $j = 1,\ldots,n$, where $dC_k/\partial v_j$ is the (marginal) effect of the kth consumption activity on the $j$the environmental variable, and there must be equality for some j, since otherwise the value of μ could have been chosen smaller than ρ^0, a contradiction. On the other hand, we have that

$$\sum_{k=1}^{L} w_k \frac{\partial C_k^h}{dq_h} \geq 1,$$

and if the inequality was strict, the values of $w_1,\ldots,w_L$ could be reduced so that the remaining inequalities could be satisfied for a smaller value of μ, once again giving a contradiction. We thus have that

$$\rho^0 = \min_{w \in \mathbb{R}_+^L, w \neq 0} \frac{\max_j \sum_{k=1}^{L} w_k \frac{\partial C_k}{\partial q_j}}{\sum_{k=1}^{L} w_k \frac{\partial C_k}{\partial q_h}}.$$

Since the quantity on the right hand side does not change if the weight vector w is multiplied by a positive scalar, we may as well restrict the minimum to w satisfying $\sum_{k=1}^{L} w_k = 1$, and consequently, we have that $\rho^0 = \rho^1$ as contended. □

6. An example: An emission-based index of relative environmental effect of Danish consumption

In the approach to measuring environmental effects of consumption via DEA, the consumption activities are viewed as desirable outputs of the economy, as end products in a technology which describes the interplay between economic activities and the environment; therefore inputs are the various environmental effects of the consumption activities. The analogy between ordinary production of goods from other goods, and the present case of producing economic "goods" with the necessary by-effects of giving rise to environmental "bads", is reasonable as far as the latter are quantities which should be as small as possible for any given level of output (consumption). On the other hand, it goes without saying that some of the implicit assumptions in an ordinary productivity analysis, namely that the technology behind the actually achieved results is the same for all units (in this case, consumption activities), cannot reasonably be upheld. On the other hand, this assumption is only needed in possible applications of the productivity analysis to the control of the individual units, not for the construction of productivity indices using DEA.

Below, we illustrate the method by some computation using Danish data from xxxx. For the first run, we use aggregated data showing the emissions in tons per millions of DKR economic activity. These aggregated data are shown in Table 1.

Table 1: Emissions in tons per million Dkr., Denmark 1998.

	CO2	SO2	NOx	CO	CH4	N2O	NMVOC	NH3
Food	39,3190	0,064781	0,174453	0,117144	0,633230	0,071199	0,030654	0,333979
Beverages and tobacco	20,0370	0,035182	0,065033	0,051208	0,079953	0,008769	0,010056	0,039008
Clothing and shoes	12,2500	0,016105	0,042174	0,047304	0,009038	0,000762	0,008392	0,001700
Housing	9,73500	0,016691	0,036100	0,031859	0,004809	0,000431	0,007924	0,000553
Electricity and heating	603,0960	0,763201	1,262908	3,144886	0,469315	0,018633	0,275617	0,056594
Furniture, household services etc.	17,8420	0,022242	0,062647	0,069116	0,010570	0,000929	0,017812	0,001582
Medicines, health exp. etc.	15,0350	0,020623	0,049803	0,058844	0,013535	0,001198	0,010522	0,003421
Other transport and communication	146,8360	0,048009	0,941837	5,176978	0,059784	0,019821	0,919389	0,003063
Leisure and entertainment, travelling	25,0940	0,034509	0,084193	0,078246	0,037384	0,003851	0,032856	0,014656
Other goods and services	17,5100	0,025022	0,059771	0,056085	0,054481	0,005755	0,010708	0,024846
Marketed individual public consumption	13,7930	0,019791	0,045051	0,055153	0,011841	0,001049	0,010219	0,002879
Non-marketed individual public consumption	17,5020	0,024108	0,055207	0,041907	0,018131	0,001495	0,008032	0,004625
Collective public cons.	17,3510	0,021917	0,090382	0,069445	0,010655	0,001090	0,016447	0,002463
Investments	22,5740	0,040876	0,095967	0,081490	0,012670	0,001377	0,021794	0,002880

Source: Data computed by Statistics Denmark.

We have chosen aggregate data in order to get a result which is of limited size and as such easier to comprehend. The aggregation has the additional advantage of reducing the dependence on outliers; indeed, minor activities may dominate several or all of the individual consumption activities, something which is largely avoided when domination can only be carried out by larger, aggregate consumption activities.

The efficiency scores (and other information) are shown Table 2[2] The table exhibits the relative efficiency index of the activities in Table 1 in the column named “scores”; thus, the index of food and beverages (no.10) is 27%, meaning that the actual emissions of the production leading to this activity would have to be reduced to 27% of its actual state, keeping the proportions of the emissions, if this activity should be as little polluting as the best in the sample. The following columns show the implicit weights used for this activity; here only the emission of CO should be included if the system of weights are to be as favorable to this activity as possible (even so its emission should be drastically reduced). Finally, the last column shows the benchmark which in this case is a single consumption activity (namely N0.40, housing); in other cases, the benchmark may be a weighted average of several activities.

Table 2. Relative environmental effects (scores) and implicit weights of emissions for aggregate consumption activities

Consumption activity	Score (%)	CO2	SO2	NOx	CO	CH4	N2O	NMVOC	NH3	Benchmarks
Food	27,20	0,00	0,00	0,00	8,54	0,00	0,00	0,00	0,00	4(1,00)
Beverages.	78,80	0,00	0,00	0,00	0,00	0,00	0,00	99,44	0,00	4(1,00)
Clothing	103,64	0,00	62,09	0,00	0,00	0,00	0,00	0,00	0,00	6
Housing.	286,08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	8,32	12
Electricity	2,88	0,00	0,00	0,00	0,00	0,00	0,00	3,63	0,00	4(1,00)
Furniture	73,64	0,00	0,96	0,00	0,00	0,00	0,00	0,00	22,16	3 (0,53) 4 (0,47)
Medicines.	79,34	0,00	39,32	3,80	0,00	0,00	0,00	0,00	0,00	3 (0,56) 4 (0,44)
Transport	34,24	0,00	20,17	0,00	0,00	0,00	0,00	0,00	10,31	3 (0,43) 4 (0,57)
Leisure	47,76	0,00	26,68	0,00	1,01	0,00	0,00	0,00	0,00	3 (0,36) 4 (0,64)
Other goods and s.	74,00	0,00	0,00	0,00	0,00	0,00	0,00	93,39	0,00	4 (1,00)
Marketed ind.pub.cons..	83,58	0,00	41,42	0,18	0,00	0,00	0,00	0,00	0,00	3 (0,25) 4 (0,75)
Non-marketed ind.pub.cons.	98,66	0,00	0,00	0,00	0,00	0,00	0,00	24,50	0,00	4 (1,00)
Coll.pub.cons.	74,20	0,00	42,75	0,00	0,00	5,92	0,00	0,00	0,00	3 (0,73) 4 (0,27)
Investments	43,12	0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,00	4 (1,00)

As it was said above, since the analogy with ordinary production should not be strained, the benchmarks are probably of minor importance in the context of relative environmental effects. However, a closer scrutiny of the results, in particular an identification of the undominated activities, may be useful for a refinement of the computation, adding restrictions on the weights employed as well as on the activities usable as potential benchmarks.

In the present computation, there are only two undominated activities, namely “Clothing” and “Housing”. The latter is far ahead of the rest, since the score (which in the table is the superefficiency score, showing how much the emissions can be increased

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[2] Computations were carried out using the DEA software EMS (Efficiency Measurement System) developed by H.Scheel, see www.wiso.uni-dortmund.de/lsfg/or/scheel/ems/).

Table 3. Indices for GWP and Acidification for aggregate consumption activities, Denmark 1998

Consumption activity	GWP index	Acidification index
Food	74.688604	24450.48318
Beverages	24.434403	4258.067855
Clothing	12.676018	1268.466712
Housing	9.969599	1078.304548
Electricity	618.727845	42708.59619
Furniture	18.351960	1802.481378
Medicines	15.690615	1606.143582
Transport	154.235974	21405.03449
Leisure	27.072874	3231.603381
Other goods and s.	20.438151	3151.867727
Marketed ind.pub.cons.	14.366851	1457.956881
Non-marketed ind.pub.cons.	18.346201	1848.898497
Coll.pub.cons.	17.912655	2452.161565
Investments	23.266940	2894.338395

Source: Data computed by Statistics Denmark

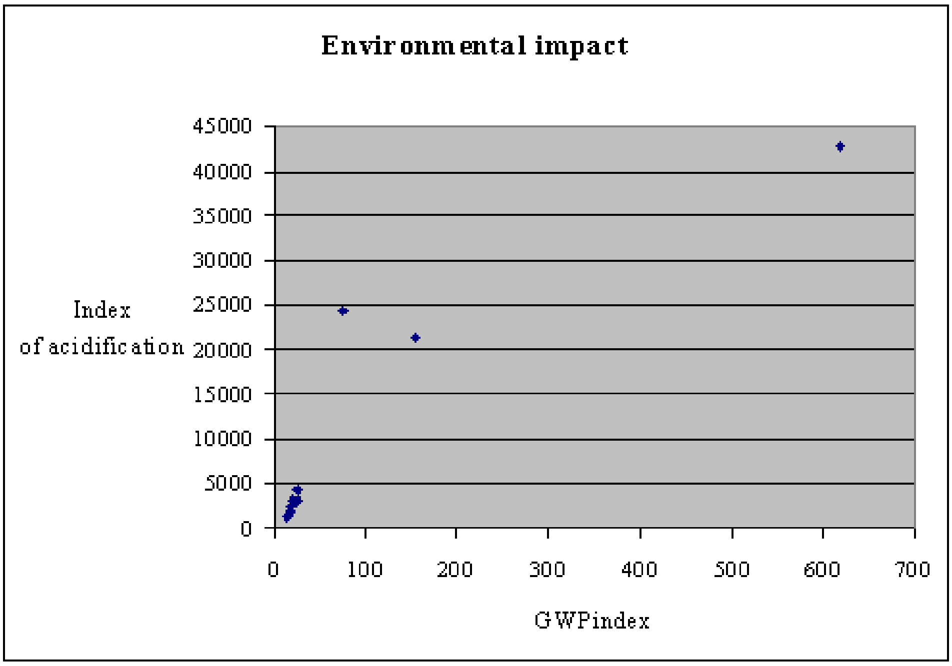
Table 4. Relative environmental effects (scores) and implicit weights of environmental impacts for aggregate consumption activities

Consumption activity	Score (%)	GWP index	Acidification index	Benchmarks
Food	13.35	1	0	4 (1.00)
Beverages	40.80	1	0	4 (1.00)
Clothing	127.15	1	0	13
Electricity	2.52	0	1	4 (1.00)
Furniture	59.82	0	1	4 (1.00)
Medicines.	67.14	0	1	4 (1.00)
Transport	6.46	1	0	4 (1.00)
Leisure	36.83	1	0	4 (1.00)
Other goods and s.	48.78	1	0	4 (1.00)
Marketed ind.pub.cons..	73.96	0	1	4 (1.00)
Non-marketed ind.pub.cons.	58.32	0	1	4 (1.00)
Coll.pub.cons.	55.66	1	0	4 (1.00)
Investments	42.85	1	0	4 (1.00)

keeping the activity undominated) is very high indeed. Examining the data for Housing, one sees that the high score is due to a very low level of NH3 emission. Similarly, the activity “Clothing” is low in emission of SO2. Adding restrictions on the weights which prevent the choice of full weight on a single low (perhaps exceptionally low) emission could possibly give a more realistic picture.

An analysis of environmental effects using impact indices. Although, as it was said above, there are as yet no data available to assess the actual environmental effects (as distinguished from the emissions of different types) of consumption activities, one can perform an analysis corresponding to that given above with two indices which are currently computed as an indication of the effects on the environment. Since the two indices, one measuring GWP and the other one measuring the acidification caused by emissions in the national economy, are constructed as linear combination of the emission series (in Table 1), we have not really moved beyond the analysis of emission data, and it can be discussed whether the partial aggregation with fixed weights is justified; however, we have chosen to include this analysis as a further illustration of the approach.

The two series are shown in Table 3 and the results of the DEA analysis in Table 4. Not surprisingly in view of what we have already seen, the activity “Housing” is efficient and in this case of only two indicators, it is the only one[3]. This is also illustrated by the plot of the two series in Table 3 presented in the diagram. The “efficient” activities are situated close to the origin; far out in the diagram are the activities of energy consumption and transportation.



Incidentally, the figure shows also that a comparison of different consumption activities based on their impact on the environment in many cases will give few surprises, since certain activities are so obviously polluting while others are not. Therefore, the techniques developed in the previous sections may probably be more gainfully employed in comparing the consumption patterns of different segments of the population than comparing different types of consumption. This seems to be a natural next step for research along the lines sketched in this paper.

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[3] Omitting this activity from the analysis will not change the picture much; only now “Clothing” becomes the unique efficient activity dominating the rest.

7. Concluding comments

In the previous sections we have considered a possible approach to the task of assigning environmental impact to consumption activities. This approach consisted of a multidimensional cost assignment followed by a construction of a relative index using the DEA methodology. As mentioned already, the approach is still in need of some perfection, and this in several respects:

First of all, the computations which can be carried out at present, using available data, are restricted to the relationships between consumption activities and emissions, and they are based on an assumption of constant returns to scale, which makes must of the considerations of cost allocation trivial. The interesting aspects of the approach will emerge when it is applied to non-linear relationships between consumption an environmental effects, and in this respect, the practical application is still to be done.

Secondly, it the theoretical aspects, the notion of a vector valued cost allocation problem is still somewhat restrictive, since what we would be dealing with in the general case is not vector cost functions but set-valued mappings which to every array $(q_1, \ldots, q_n)$ of activities assings a set $\Phi(q_1, \ldots, q_n) \subset \mathbb{R}^S_+$ of environmental impacts (possibly with certain well-behavedness properties, and satisfying $\Phi(q_1, \ldots, q_n) + \mathbb{R}^S_+ \subset \Phi(q_1, \ldots, q_n)$); in other words, we should take into account the possible tradeoffs between different environmental indicators, even at a given level of economic activity. Clearly the methods of cost allocation treated in this paper are not immediately applicable to this situation; on the other hand, extensions (roughly corresponding to the change of frame of reference from the context of TU games to that of NTU games) suggest themselves. We shall, however, not at present follow up on this, which is a topic of future research.

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(xlv) This paper was presented at the International Workshop on “New Ports and Urban and Regional Development. The Dynamics of Sustainability” organised by the Fondazione Eni Enrico Mattei, Venice, May 5-6, 2000.

(xlvi) This paper was presented at the Sixth Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, January 26-27, 2001

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