

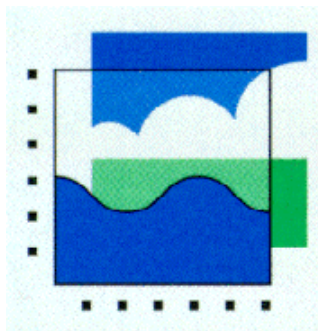
Material flows and economic models: An analytical comparison of SFA, LCA and equilibrium models

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Material flows and economic models:

An analytical comparison of SFA, LCA and equilibrium models

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Abstract

The growing concern for environmental problems in the current economy has spurred the study of the way materials and substances flow through the economy, resulting in many different types of analysis. Since all of these have their merits and shortcomings, much of the present theoretical research seems to be focusing on combining the best aspects of each model type into an integrated model. The aim of this paper is to make a first step in bridging the gap between the various types of analysis of material flows in the economy, by discussing the main differences and similarities of three often employed model types: Substance Flow Analysis, Life Cycle Assessment and Economic Equilibrium Analysis. Instead of submitting each model to a lengthy theoretical discussion, we apply them to a single, hypothetical example of a pollution problem. By doing so we are able to evaluate the differences and similarities of the methods and results of the model in a practical way.

Key words

Material flow models, economic models, substance flow analysis, life cycle assessment, partial economic equilibrium analysis

1. Introduction

Many environmental problems can be directly related to flows of substances, materials and products through the economy. Several methods for describing physical flows have been developed to study such flows, but these include no description of economic mechanisms (allocation, optimization, substitution) or costs and benefits. Economic models, on the other hand, have mainly focused on abstract externalities and do not explicitly describe the flows and transformation of materials. It appears that an integration of these two classes of models is desirable.

This integration has been attempted a number of times. Evidence is provided by studies such as Ayres & Kneese (1969), Leontief (1970), Victor (1972), Perrings (1987), Ruth (1993) and Faber & Proops (1997). None of these attempts has been completely satisfying, however. The issue at stake is one of conflicting requirements. On the one hand, the models should be complete, in the sense of covering extraction, production, consumption and waste treatment; resource availability and pollution; bulk materials and micro pollutants; and so forth. On the other hand, the models should be operational, in the sense of having a low data demand and being easy to construct and run in practice. This second requirement has stimulated the development of a class of rather restricted models. We mention: substance flow analysis and material flow analysis, life cycle assessment, risk analysis on the physical side, and equilibrium models and macro models on the economic side. These models have modest pretensions in the sense of not aiming to provide an ultimate answer to policy questions. A natural

question is then to which extent the results thereby obtained are valid, to which extent expansion of one restricted model by another one is possible and useful, and where the practical boundaries of application and domain-extension are.

There are theoretical surveys of such partial models (see for instance Kandelaars, 1998). Such overviews usually contain a catalogue of abstract properties, like primary object and main assumptions. Here, a complementary approach is presented to provide another perspective: that of showing the consequences of the differences between these models by applying them in a hypothetical case study. Three models are applied: substance flow analysis (SFA), life cycle assessment (LCA) and partial economic equilibrium analysis (PEA). Clearly, these three are not the only models that are used to study economy-material interactions. There is a wide range of other models, but we feel that the three models that are discussed in this paper are representative for the typical differences that exist between the various model types. A complete list of models would also include general equilibrium models, macro models, and economic input-output models. However, both general equilibrium models (including CGE models) and macro models (based on micro behavior) may be viewed as extensions of the partial equilibrium model that is discussed in section 3.3. Furthermore, economic input-output models are technically similar to the material flow analysis of section 3.1.

All models and model classes examined must be seen in relation to a set of questions. Typical questions are:

- What is the relation between flows of materials and economic phenomena, like demand and supply decisions?
- To what extent are certain policy measures capable of influencing material flows?
- Will any trade-off between flows of different materials occur when introducing those policy measures through existing interdependencies?

The structure of this paper is as follows. Section 2 introduces the aspects that are used as criteria for judging the different models, and gives specifications of the example that is to be elaborated in the discussion of the different models in the model survey of Section 3. A synthesis of findings is presented in Section 4, and Section 5 concludes with prospects for a further integration of these models.

2. The example

The various model strategies employed by researchers studying material-economy interactions are different in many respects. Most apparent are the technical differences, such as mathematical methods, data requirements and demarcation of the problem. Less obvious, but possibly more important, are basic differences in assumptions and goals. Assumptions related to the role of materials in the economy, to the rigidity of economic relations, to the restrictiveness of physical constraints, and to the way the economy and the environment interact, can differ considerably. Many of these differences are not in the first place determined by the nature of the problem that is studied, but can often be tracked down to the fact that environmental science is a field where many scientific disciplines meet.

Given the wide range of differences, it is unlikely that an abstract discussion of the models, by reviewing their underlying assumptions, technical specifications and possible applications, would give a complete insight into the crucial differences and similarities between the models. The result of such an exercise would probably be an enumeration of characteristics from which generalizations are difficult to make. Therefore, we discuss the models by applying each to a single example of a material-based environmental problem. This allows us to study the models in their 'natural environment', which facilitates comparison. By using an example as explanatory tool, the problem of the model variety is shifted to the task of constructing an example that is rich enough to capture the essential elements of each model, and at the same time simple enough for the results to be easily interpretable. Therefore, the example used in this paper is quite simple in structure but elaborate in detail.

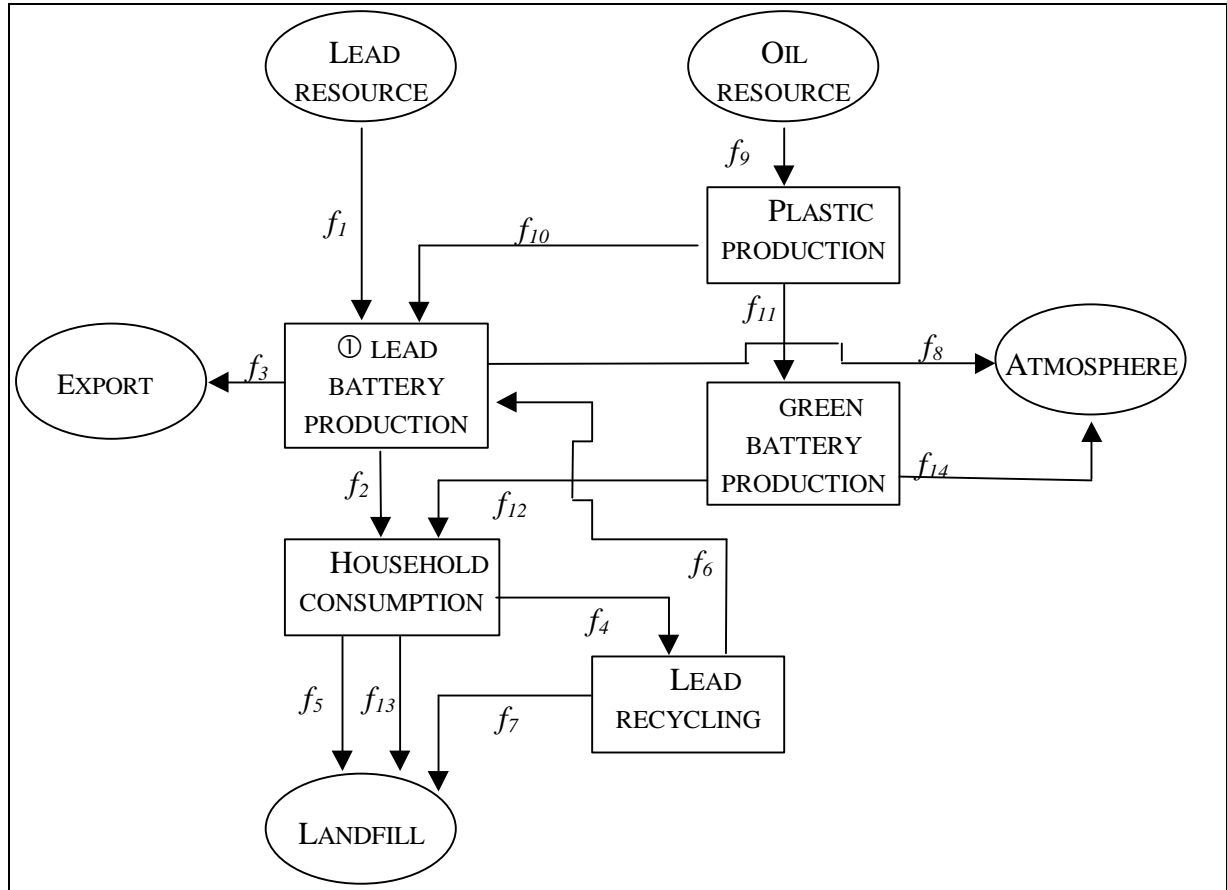


Figure 1. Flow diagram of the battery example. Legend: arrows represent flows, boxes processes and ellipses mines and sinks. The processes are identified by circled numbers.

The structure of the example is depicted in Figure 1, which describes the relations between 10 different ‘nodes’ involved in production, consumption and post-use processing of automobile batteries. It is an example of a metal-pollution problem, since most automobile batteries consist for the larger part of lead that can be hazardous when released to the environment. The advantage of using a metal related problem in the example is — besides the relevance for environmental policy — that the characteristics can easily be modeled. Recycling of metals, for instance, is often a straightforward process of which the produce can be used for the production of the original product.

As can be seen from Figure 1, stocks of materials or products do not exist in the example. The reason for this assumption is that including stocks would necessitate description of dynamic relations within and between nodes. Including dynamics would reveal differences in the way the models handle time related issues, but would do so at the price of a large increase in the complexity of the example. A second important simplification is that in the example materials are the single factor of production. Other factors, such as labor and capital are excluded from the analysis.

We assume that batteries come in two types: lead batteries and ‘green’ batteries. The former is the ‘traditional’ battery that consists of a lead core and a plastic casing. The latter is its supposedly ‘environmentally friendly’ substitute that, for sake of simplicity, consists merely of plastics. Lead is produced in the mining sector and plastics are produced by the plastic producing sector, which obtains its raw materials from the crude oil producers. We assume that crude oil is contaminated with a small

amount of lead. Consequently, plastic battery cases and green batteries contain a small fraction of lead. This lead serves no purpose, so its use is unintentional.

Both types of batteries are used by households. Additional to domestic demand, part of the lead batteries are exported. For simplicity, we assume that the green batteries are all consumed domestically. After use, batteries are disposed of by the households. Used green batteries have only one destination: they are dumped in landfills. For lead batteries there is, besides dumping, the possibility of collection of the battery and recycling of (part of) the lead. Unrecovered lead of collected lead battery, as well as the plastic casings are dumped. The recycled lead is sold to the lead battery producing firms. Disposal of batteries is not the only source of pollution in this example. Production itself is also polluting. Producing green battery generates flue gas emissions containing hydrocarbons and a small amount of lead. Lead is also emitted to the atmosphere through production of lead batteries.

The initial values of the flows between the nodes are shown in Table 1. These values are the starting point of the application of each of the models in the next section. It can be seen that in the initial situation 75% of the batteries are lead batteries. Only one out of every three lead batteries is collected, and from each collected lead battery 80% of the lead is recovered. The bulk of the lead waste generated in the economy is landfilled. Compared to lead dumping, the emissions of lead to the atmosphere are small.

Table 1. Initial Values of Material Flows.

Flow	Name	Value	Unit
f_1	mined lead ore	800	kg/yr
f_2	domestically sold lead batteries	150	units/yr
f_3	exported lead batteries	45	units/yr
f_4	collected used lead batteries	50	units/yr
f_5	dumped used lead batteries	100	units/yr
f_6	recycled lead	200	kg/yr
f_7	dumped recycling residual	55	kg/yr
f_8	air emissions lead battery production	25	kg/yr
f_9	crude oil	75	kg/yr
f_{10}	plastic battery casing	195	units/yr
f_{11}	plastic for green batteries	55.5	kg/yr
f_{12}	domestically sold green batteries	50	units/yr
f_{13}	dumped used green batteries	50	units/yr
f_{14}	air emission green battery production	5.5	kg/yr

These initial values imply that each lead battery consists of 5 kg lead and 0.1 kg plastic (the battery casing), while a green battery consists of 1 kg plastic. We assume that crude oil, plastic, and the emitted exhaust gas from the green battery production contain 1% lead. The initial values are chosen such that mass balance holds throughout the system.

In our example, production and consumption of batteries generates three types of environmental damage:

- depletion of resources (lead ore and crude oil)
- air pollution (from lead battery production and from green battery production)
- landfill of waste (by households and by the recycling sector).

Congruous to these three problems, we discern three policy objectives for the environmental policy maker:

- (i) reduction of the use of virgin materials,
- (ii) abatement of emissions to the atmosphere,
- (iii) reduction of waste disposal on landfill sites.

In the next section three different models are employed to analyze the policies for attaining these environmental goals.

3. Application of the models

In this section the three selected concrete models for analyzing the relationship between economy and environment — MFA/SFA (Section 3.1), LCA (Section 3.2) and PEA (Section 3.3) — are discussed separately and will be applied to the example described above. In Section 3.4 the results of the models are compared.

3.1 Material flow analysis and substance flow analysis (MFA/SFA)

Method

MFA/SFA modeling is based on input-output analysis (IOA), as originally developed by Leontief (1966), and extended in various directions (see Miller & Blair (1985) for a standard reference, and Duchin & Steenge (1998) for a survey of environmental extensions). Input-output analysis is a standard economic tool describing mutual deliveries between sectors, in terms of money or in terms of volumes of goods. It is used mostly on the national level to obtain a picture of the structure of the economy and the mutual relations between economic sectors, and to identify the major flows of money and/or goods within the economic system. It is used as an accounting tool: the mutual deliveries are “measured” and summarized in a table, the input-output table. It is also used as a model, *i.e.* input-output analysis, mainly to predict the changes in sectoral activity as a result of an increase in the final demand for one specific good. This is the so-called impact analysis by means of Leontief multipliers.

An input-output table contains data that are obtained by observation. Although the data obviously are the result of a complicated mix of behavioral and technical considerations, no attempts are being made to explain the data, or to separate behavior from technology. Moreover, in doing input-output analysis, the data is treated quite mechanically as technical coefficients. Non-linearities, for instance due to decreasing marginal utility or production, are not considered. Input-output analysis therefore is a rather restricted type of model. In principle it excludes environmental concerns. However it should be noted that the concept of input-output analysis has been extended by many authors to include environmental aspects; see, *e.g.*, Ayres & Kneese (1969), Leontief (1970), Victor (1972), Perrings (1987), Idenburg (1993), Van der Voet (1996), Heijungs (1997).

The MFA/SFA modeling, which originates from considering the economy in the physical dimension as described by Ayres (1989) in the concept of industrial metabolism, is rather similar to IOA and therefore is sometimes referred to as ‘environmental input-output analysis’ (Schröder, 1996). The mass balance principle is the core rule in MFA/SFA. Applying it rigorously enables one to spot hidden or unexpected flows and emissions, and to detect accumulation of stocks in the economy or the environment, which may cause problems at some future time. Static and steady state models are used to assess the origins of pollution problems and, in a manner very comparable to IOA, to estimate the impacts of certain changes in the economic materials management (*e.g.* Baccini and Bader, 1996). Dynamic models are used to estimate the development of emissions and waste generation in future (*e.g.* Bergbäck and Lohm, 1997). The SFA matrix of coefficients is not drawn up on a sector-by-sector basis, but on a commodity-by-commodity basis. The SFA matrix of coefficients therefore is square, but larger than the IOA matrix.

MFA is used to comment on the materials throughput or the materials intensity of national economies, important sectors or large functional systems and therefore concentrates on bulk or mass flows. SFA is

used to identify the causes of specific pollution problems in the economy and find possibilities for amending or preventing those problems, and therefore is concerned with the flows of specific substances. Generally MFA stops at the border of the environment, while SFA also considers the environmental flows. For an overview, see for example Bringezu et al. (1997). A specific form of SFA is the so-called environmental fate modeling. This type of model concentrates on environmental flows. It is based on physico-chemical properties of substances on the one hand and environmental characteristics on the other (e.g., Mackay, 1991). Such a fate model can be linked to risk assessment models, thereby expanding the scope of SFA (Guinée et al., forthcoming).

Application

A typical SFA application would start from the environmental side. In the example described in Section 2 environmental problems related to lead are mentioned. For these problems, ‘problem flows’ can be defined, in line with Section 2: (1) the required virgin input of lead (f_1), (2) the emissions of lead to the atmosphere (f_8 and f_{14}), and (3) the landfill of final waste containing lead (f_5, f_7 and f_{13}). Note that depletion of oil stocks and hydrocarbons emissions are out of sight; for this an additional SFA for oil and oil products is required which is not attempted here.

As a first step, the origins of these problem flows could be assessed. In this paper we skip this, because there is only a single source for the system: f_1 , the mining of lead ore. In a real case, there may be many sources so going through an origins analysis could be useful.

The second step then is to find the most promising directions in which to look for a solution of the lead related problems. The three policy objectives described in Section 2 are translated into fairly extreme ‘measure packages’ in order to explore the potential usefulness of such directions:

- (i) As a possibility to reduce virgin lead extraction, a complete substitution of lead batteries to green batteries. The lack of economic mechanisms in the SFA model forces us to specify two extremes for the development of lead battery production: (ia), production of lead batteries remains at the same level, batteries are exported, and (ib), production of lead batteries is closed down altogether.
- (ii) In order to reduce lead emissions to air, end-of-the-pipe emission reduction by technical means to 1% of the present level is assumed, not influencing supply and demand of lead batteries or green batteries.
- (iii) In order to prevent landfill, the collection of discarded batteries is boosted to 100%, and transformation of old batteries into secondary lead to 90%.

The data of **Error! Reference source not found.** are then translated into IO-like equations. Letting y -variables represent the amount of lead contained in the f -flows, the set of equations contains exogenously fixed variables of the type $y_1 = a$, dependency equations of the type $y_2 = b \times y_1$, and balancing equations such as $y_3 = y_2 - y_1$.

Exogenously determined variables are the domestic demand for lead batteries (y_2), the domestic demand for green batteries (y_{12}), the total production of lead batteries ($y_2 + y_3$), and the matching total production of plastic casings for the lead batteries (y_{10}). See Table 2 for an explanation of the variables and coefficients.

$$\begin{aligned} y_2 &= f \times (a + c \times b) \\ y_{12} &= g \times (a + c \times b) \\ y_2 + y_3 &= h \times (a + c \times b) \\ y_{10} &= h \times c \times b \end{aligned}$$

Dependency equations are formulated for the emissions to the atmosphere from both the lead battery production (y_8) and the green battery production (y_{14}), for the collection of discarded lead batteries (y_4),

for the recovery of secondary lead from the collected lead batteries (y_6) and finally for the dumping of discarded green batteries (y_{13}):

$$\begin{aligned}y_8 &= i \times (y_1 + y_6) \\y_{14} &= j \times y_{11} \\y_4 &= k \times y_2 \\y_6 &= l \times y_4 \\y_{13} &= m \times y_{12}\end{aligned}$$

This set is completed by so-called balancing equations to calculate the remaining lead flows, at the same time enforcing mass balance. In this way, y_1 is calculated, the required amount of freshly mined lead, as well as y_5 , the amount of lead batteries being discarded by consumers. The assumption here is that battery consumption is in a steady state and consequently there is no stock change. In this respect the example is shortcoming: signaling and modeling stock changes is an important part of SFA. Also y_7 (*i.e.* the amount of lead not-being-recovered ending up at the landfill site after all), y_9 (*i.e.* the demand for crude oil in terms of its lead contamination) and finally y_{11} (*i.e.* the required amount of plastic for the production of green batteries) are calculated by balancing equations.

$$\begin{aligned}y_1 &= y_2 + y_3 + y_8 - y_6 - y_{10} \\y_5 &= y_2 + y_{12} - y_4 - y_{13} \\y_7 &= y_4 - y_6 \\y_9 &= y_{10} + y_{11} \\y_{11} &= y_{12} + y_{14}\end{aligned}$$

Table 2. Initial value of the SFA modelling coefficients.

Coefficient	Meaning	Value	Unit
<i>a</i>	amount of lead in 1 lead battery	5	kg
<i>b</i>	weight of 1 plastic battery case	0.1	kg
<i>c</i>	lead content of plastic	0.01	kg/kg
<i>d</i>	weight of 1 plastic green battery	1	kg
<i>e</i>	total demand for batteries	200	units
<i>f</i>	internal demand for lead batteries	150	units
<i>g</i>	total demand for green batteries	50	units
<i>h</i>	total production of lead batteries total number of battery cases produced	195	units
<i>i</i>	emission coefficient lead battery industry	0.025	kg/kg
<i>j</i>	emission coefficient green battery industry	0.0991	kg/kg
<i>k</i>	fraction discarded lead batteries collected for recycling	1/3	-
<i>l</i>	fraction lead recovered from collected batteries	0.7998 ¹	-
<i>m</i>	fraction discarded green batteries landfilled	1	-

Solving the set of equations leads to a result that is in line with the example as it is presented in Section 2. In order to calculate the impacts of the three measure packages, some changes must be made in this set of equations.

Measure package (i) is the substitution of lead batteries by green batteries. Complete substitution is assumed. Package (ia) leaves the production of batteries intact and channels this production directly to

¹ 0.8 of lead in batteries, lead from plastic casing is not recovered.

foreign countries. Under package (ib) battery industry is closed down. This leads to the changes in the variables and coefficients as listed in Table 3.

Table 3. Change of SFA modeling coefficients under measure package (i).

Coefficient	Initial	Package (ia)	Package (ib)	Unit
f	150	0	0	units
h	195	195	0	units
g	50	200	200	units

Package (ii) refers to technical air emission reduction. This only leads to two modifications in the set of equations compared to the basic model, modifying the emission coefficients from the industries involved to obtain an emission reduction by 99%; see Table 4.

Table 4. Change of SFA modeling coefficients under measure package (ii).

Coefficient	Initial	Package (ii)	Unit
i	0.025	0.00025	kg/kg
j	0.0991	0.000991	kg/kg

Package (iii) contains the increase of lead recycling. Both the collection of discarded lead batteries and the recovery of lead from the collected batteries is boosted; see Table 5.

Table 5. Change of SFA modeling coefficients under measure package (iï).

Coefficient	Initial	Package (iii)	Unit
k	0.333	1	-
l	0.7998	0.8998	-

The result of these packages for the identified problem flows is summarized and compared with the present situation in Table 6.

Table 6. Prediction of the size of the problem flows SFA under the different measure packages.

Flow	Name	Initial	(ia)	(ib)	(ii)	(iii)	Unit
f_1	mined lead ore	800	1000	0	775	325	kg/yr
f_8	air emission lead battery production	25	25	0.22	0.25	25	kg/yr
-	landfilled lead	551	2	2	551	75.5	kg/yr

Table 6 shows that under the regime of package (ia) the requirement for virgin lead is highest. This is due to the fact that the production of lead batteries is maintained but there is no input of secondary lead since domestic recycling has disappeared completely. Package (ib), including closing down the battery industry, requires no virgin lead at all. Packages (ia) and (ib) also differ regarding the air emissions: in (ia), the emissions remain at the present level since the production of lead batteries still continues, but in (ib) merely the emission from the plastics industry remains. The landfill problem will be solved by both (ia) and (ib). It appears therefore that the question of how the battery industry will react is very important for the effects of such a substitution. With an SFA model this question cannot be answered at all. In all, package (ib) seems the best option altogether from the point of view of solving the lead problems. However, the question is what the economic impacts will be, and whether there will be significant environmental side-effects from this substitution as a result of an increase of emissions other than those of lead. Again these questions cannot be answered with SFA.

Package (ii) appears to have a limited but altogether positive impact on the three problem flows. There is no trade-off, the air emissions will be reduced significantly and that also slightly reduces the demand for virgin lead. Economic impacts will probably be limited as well, which enhances the credibility of the SFA results.

Package (iii) has, as might be expected, a beneficial impact on the demand for virgin lead. The air emissions remain at the original level, but landfill is reduced significantly by this “closing-of-cycles” package. Here again the question is what the economic consequences will be of establishing collection schemes and recycling plants. Again, such questions cannot be answered by SFA.

Discussion

From this application of SFA to the example, we can make a summary of merits and limitations of the SFA approach.

1. With SFA, environmental problems can be related to their economic origins (such as sectors or imports; Van der Voet, 1996, p.37). This offers possibilities for the identification of potential solutions.
2. SFA is a powerful tool to assess the impacts of various potential solutions on the identified problems. Its main strong point is the quick scanning of various - feasible as well as non-feasible - options in a technical sense.
3. What is not directly readable from the above results is the fact that SFA models can handle - compared with the more complicated economic models such as treated in section 3.3 - large systems quite easily. There is no need for a restriction to small systems, in fact being comprehensive is one of the main purposes of SFA, since only then the advantages of the origins analysis and problem shifting to other parts of the chain will show.
4. SFA does not include the economic value of flows. On the one hand this simplifies the inclusion of environmentally relevant flows without economic value, such as flows of product contaminants (lead in plastics). On the other hand, this does not allow for an analysis of economic impacts at all. Neither the effectiveness, nor the economic consequences of policy instruments such as taxes or subsidies can be evaluated. Such economic consequences may have environmental impacts in their turn, these are of course also out of the SFA picture.
5. SFA also is blind for shifting of problems to outside the substance chain; in the example the problems related to the oil/plastics chain. The environmental consequences of substitution therefore cannot be evaluated.

All in all, SFA appears to be a handy and useful, but limited tool. Obviously, the limitations are more irksome as the proposed societal changes are larger. For small-scale substances such as metals SFA may go a long way, since the economic consequences of changes are probably minor. For the management of large-scale substances such as carbon, requiring more dramatic changes in society, SFA by itself is insufficient, although its input still can be useful.

3.2 Life cycle assessment (LCA)

Method

LCA (see Curran (1996) for a broad overview) is a tool to assess the environmental consequences of a product from cradle to grave. It is intended to support decisions with respect to purchase, improvement, design, and so on. LCAs can produce results at the level of the interventions (emissions, extraction of natural resources), at the level of impact categories (global warming, toxicity), at the level of damage to endpoints (human health, material welfare), or at the level of one single indicator. The life cycle of the product comprises in general such diverse aspects as resource extraction, manufacturing of materials and energy, manufacturing of the product, use, maintenance, and waste treatment. Capital goods are often only incorporated as far as their direct functioning is involved. For instance, not the depreciation

of the truck which is needed to transport aluminium, but only fuel needs and exhaustion gases are included. The procedures for LCA is to some extent standardized: an ISO-standard is under construction (the so-called 14.040-series), but it will concentrate on procedural matters and main lines of approach, neglecting technical details like mathematical recipes.

Main phases of the LCA procedure are:

- goal and scope definition, mainly containing a description of the exact topic, question, and approach;
- inventory analysis, concentrating on the physical exchange between product life cycle and the environment in terms of emissions and extractions;
- impact assessment, concentrating on the impacts that can be associated with the aforementioned emissions and extractions;
- interpretation, dealing with uncertainty analyses, preferences, aspects of feasibility and so on.

LCA focuses on the function of a product, not on the product itself. An example of such a function is "lighting a room with a certain amount of light for 3 hours". Usage of this so-called functional unit enables a comparison of product alternatives and (re)design of products and/or processes on the basis of the function that is to be delivered by the alternatives. It also implies the study of the so-called product system, from the cradle to the grave. LCA associates a set of numbers (or one single index) for each alternative that fulfils the specified product function. The numbers have only meaning in a comparative sense. The comparison may be across a range of products fulfilling comparable functions/services (*e.g.* light bulbs of different types), of a product function within an entire set of product functions (*e.g.* laces as a part of shoes), or inside a product life cycle (*e.g.* the production stage or the paint within the whole life cycle of cars). Due to uncertainties and assumptions (in data, models, *etc.*) throughout the entire procedure, the outcomes of an LCA should be interpreted with great care, and preferably include extensive sensitivity analyses.

LCA encompasses various types of substances and environmental impacts. The inventory analysis of all LCAs will include extractions of metal ores, refinement and production of metals, intended and non-intended application in products and intermediates, processing of metal-containing waste, and releases of metals to the atmosphere, to watercourses, or to soil. Furthermore, LCAs may be performed of products that are made of metal or that contain it. Aluminium cans and batteries are famous examples. There are no special requirements to including metals in an LCA. Special problems that may be encountered are the fact that emissions are often specified in an aggregated way (like "heavy metals" instead of "Cd", "Cr", *etc.*), and that the specification of these releases is often not given (like "Cu" instead of "CuSO₄", "CuCl₂", *etc.*).

A final remark is that one cannot make an LCA for a metal or any other material. Since an LCA is coupled to an application of that metal, many LCAs of metal-containing products may be conducted. On the other hand, all these products are associated with non-metallic substances, so that the LCA of a metal-containing product contains information on flows of sulfur, carbon and many other substances.

Application

The data of the flows of products and materials have been manipulated into standard LCA process data according to the normal procedures. These are:

- data are usually normalized to an arbitrary but round output quantity (like 1000 batteries instead of 150 batteries per year); to safeguard transparent comparison with SFA and PEA this optional step has not been carried out;
- inputs of flows have been indicated by negative numbers, outputs by positive numbers;
- the order of the flows has to be changed into one set of economic flows (which flow from or to other processes) and one set of environmental flows (which flow from or to the environment).

- multiple processes (e.g. joint production, waste treatment including recycling), must be split² into independent single processes; this applies to process where a so-called allocation factor (λ) is used to allocate the recycling residual over treatment of collected used lead batteries (process a) and production of recycled lead (process b) and to process where a possibly different allocation factor (μ) is used to allocate the crude oil over production of plastic casing of lead batteries (process a) and production of plastic for green batteries (process b);
- the consumption process is separated into consumption of lead batteries and consumption of green batteries;
- the function of the consumption processes needs to be specified; this enters the table as flows a_7 and a_8 .

This leads to Table 7. One point needs clarification. LCA studies material flows associated with a functional unit of product. The calculated flows do therefore not represent the total flows in the economy-environment system. For this reason, the calculations are all done in terms of different symbols (a and b instead of f).

Table 7. Table of process data for LCA

Flow	Meaning	①	a	b	a	b	a	b	Jnit
a_1	total sold lead battery	$-f_2+f_3$	$-f_2$	0	0	0	0	0	units
a_2	collected used lead battery	0	f_4	0	$-f_4$	0	0	0	units
a_3	recycled lead	$-f_6$	0	0	0	f_6	0	0	kg
a_4	plastic lead battery casing	$-f_{10}$	0	0	0	0	f_{10}	0	units
a_5	plastic	0	0	0	0	0	$-f_{11}$	f_{11}	kg
a_6	total sold green battery	0	0	$-f_{12}$	0	0	f_{12}	0	units
a_7	lead battery use	0	g_1	0	0	0	0	0	yr
a_8	green battery use	0	0	g_2	0	0	0	0	yr
b_1	lead ore	$-f_1$	0	0	0	0	0	0	kg
b_2	dumped used lead battery	0	f_5	0	0	0	0	0	units
b_3	recycling residual	0	0	0	λf_7	$(1-\lambda)f_7$	0	0	kg
b_4	air emission lead battery production	f_8	0	0	0	0	0	0	kg
b_5	crude oil	0	0	0	0	0	$-\mu f_9$	$-(1-\mu)f_9$	kg
b_6	dumped used green battery	0	0	f_{13}	0	0	0	0	units
b_7	air emission green battery production	0	0	0	0	0	f_{14}	0	kg

We need to choose the allocation factors λ and μ ; this is done according to Table 8.

Table 8. Choice of coefficients in LCA

Coefficient	Meaning	Value	Unit
λ	for allocation of process into independent processes a and b	0.5	-
μ	for allocation of process into independent processes a and b	0.5	-

² This procedure of splitting a multiple process into two (or more) single processes is in LCA-circles referred to as the allocation step. This term may be somewhat confusing for economists, as it may wrongly suggest the incorporation of market allocation mechanisms into LCA.

The standard theory of LCA now provides a procedure to partition the table of process data into two matrices, and to calculate a list of environmental flows associated with a certain unit of function. Here we choose to do calculations for 100 years of lead battery use and 100 years of green battery use. However, to enable a comparison with the other two models, we may translate the matrix equation into a set of simultaneous equations. This requires the explicit introduction of 8 scaling parameters s , for each (single) process one. For the case of lead batteries, the set of equations is written below.

$$\begin{aligned}
s_1(f_2 + f_3) + s_{2a}(-f_2) &= 0 \\
s_{2a}f_4 + s_{3a}(f_4) &= 0 \\
s_1(-f_6) + s_{3b}f_6 &= 0 \\
s_1(-f_{10}) + s_{5a}f_{10} &= 0 \\
s_4(-f_{11}) + s_{5b}f_{11} &= 0 \\
s_{2b}(-f_{12}) + s_4f_{12} &= 0 \\
s_{2a}a_7 &= 100 \\
s_{2b}a_8 &= 0 \\
b_1 &= s_1(-f_1) \\
b_2 &= s_{2a}f_5 \\
b_3 &= s_{3a}I f_7 + s_{3b}(1 - I)f_7 \\
b_4 &= s_1f_8 \\
b_5 &= s_{5a}(-m f_9) + s_{5b}(-(1 - m)f_9) \\
b_6 &= s_{2b}f_{13} \\
b_7 &= s_4f_{14}
\end{aligned}$$

For green batteries, we only need to exchange the righthand side parameters 100 and 0 in the 7th and 8th equation. Solving the equations yields the tabulated results for lead and green batteries respectively (Table 9).

Table 9. Environmental flows according to LCA of 100 yr battery use. Third column for the lead batteries, fourth column for the green batteries.

Flow	Meaning	Lead batteries	Green batteries	Unit
b_1	lead ore	-82	0	kg
b_2	dumped used lead battery	13	0	units
b_3	recycling residual	6.5	0	kg
b_4	air emission lead battery production	2.6	0	kg
b_5	crude oil	-3.9	-15	kg
b_6	dumped used green battery	0	20	units
b_7	air emission green battery production	0	2.2	kg

Furthermore, we will be assuming that a weighting between different pollutants and resources has been set, involving weighting factors as in Table 10.

Table 10. Weights for the various environmental flows and weighted results for the LCA of 100 year batteries with lead batteries and with green batteries.

Flow	Meaning	Weight ³	Unit	Lead batteries	Green batteries	Unit
<i>b</i> ₁	lead ore	−5	1/kg	410	0	-
<i>b</i> ₂	dumped used lead battery	20	1/units	267	0	-
<i>b</i> ₃	recycling residual	3	1/kg	19	0	-
<i>b</i> ₄	air emission lead battery production	25	1/kg	64	0	-
<i>b</i> ₅	crude oil	−40	1/kg	154	600	-
<i>b</i> ₆	dumped used green battery	5	1/units	0	100	-
<i>b</i> ₇	air emission green battery production	2	1/kg	0	4	-
	Weighted total	-	-	914	704	-

We thus see that for the fulfillment of an identical function (100 years of battery use), the two alternatives products have quite different environmental flows and impacts. The lead battery system has of course many lead-related flows and impacts, but especially the oil depletion makes that the green battery alternative has serious disadvantages (in our fictitious set of weighting factors).

The hypothetical measures that were formulated in the previous subsection have been analyzed with LCA once more. Package (i), the take-over of green batteries, is not interesting with LCA, as LCA does not deal with actual market volumes, but just compares lead and green batteries on the functional level, so per year of use.⁴ Package (ii), the end-of-pipe reduction of all air emissions with 99% results in a simple calculation: the life-cycle air emissions due to production of lead batteries (f_8) and production of green batteries (f_{14}) have indeed been reduced by a factor of 0.99. Package (iii), the increase of collection of lead batteries to 100% and their recycling to 90% produces less trivial results. First we must change certain coefficients of the equations, to account for the changes in technology structure. We change the coefficient for output of collected used batteries by process *a* from 50 to 150, for output of dumped used lead batteries by that process from 100 to 0, for output of recycled lead by process *b* from 200 to 229.5, and output of recycling residual by processes *a* and *b* from 27.5 to 12.25. Table 11 shows the results. The amount of dumped used lead batteries (f_5) then drops from 20 to 0, and the amount of recycling residual (f_7) drops from 6.5 kg to 6 kg. For the green batteries, there is of course no difference.

Table 11. Summary of calculations of measures that could be considered to improve batteries.

Flow	Meaning	Initial lead batteries	Initial green batteries	(ii) lead batteries	(ii) green batteries	(iii) lead batteries	(iii) green batteries	Unit
<i>b</i> ₁	lead ore	-82	0	-82	0	-82		kg
<i>b</i> ₂	dumped used lead battery	13	0	13	0	0	0	units
<i>b</i> ₃	recycling residual	6.5	0	6.5	0	6	0	kg
<i>b</i> ₄	air emission lead battery production	2.6	0	0.026	0	2.6	0	kg
<i>b</i> ₅	crude oil	-3.9	-15	-3.9	-15	-3.9	-15	kg
<i>b</i> ₆	dumped used green battery	0	20	0	20	0	20	units
<i>b</i> ₇	air emission green battery production	0	2.2	0	0.022	0	2.2	kg
	Weighted total	914	704	851	700	646	704	-

It may appear strange that an increase of lead recycling does not decrease the depletion of lead ores. But we must bear in mind that process *a* (lead recycling) was redefined in package (iii), while process

³ The sign of the weighting factors needs some comments. Those that weight inputs are negative, because they have to convert a negative number (an input flow) into a positive number (a positive contribution to the environmental problem).

⁴ Recall that advantages or disadvantages that are related to scale are outside the linear homogeneous formalism, and hence outside the scope of LCA.

① (lead battery production) was left unchanged. Had we defined package (iii) as the increase of production of recycled lead (in favor of recycling residual) and the increase of use of recycled lead (in favor of lead ore), the depletion problem of lead would have diminished (but not much). The situation is now that the secondary lead is available for all kinds of purposes on which nothing has been said. It may replace existing uses of lead, but it may also create new types of application. This is outside the scope of LCA

An interesting result is that green batteries are per unit of function better than lead batteries, except under package (iii). Here we see one of the strengths of LCA: it studies all environmental flows and/or impacts associated with a certain function, such as batteries. Indeed, under (iii), the dumping of used lead batteries decreases so much that the alleged green alternative becomes in fact second choice, mainly through the depletion of crude oil.

Discussion

We see that the main use of LCA is in the determination of all environmental problems related to a certain unit of product. Actual market situations and scenarios are not to be approached by LCA. This restricts its scope to an identification of hot spots, and a comparative assessment of competing systems. A more systematic account follows:

1. LCA concentrates on the environmental flows and/or impacts associated with a function that may be fulfilled in different ways. As such, LCA is able to address all types of flows and/or impacts: heavy metals, pesticides, organic compounds, ores, and in principle, also noise, radiation, land use, etc.
2. LCA does not study actual market volumes. In consequence, it does not address the question of changes in market volumes as a direct or indirect result of technical or policy measures.
3. In LCA the function that a product delivers is externally imposed. Its usefulness, or its contribution to welfare is left undiscussed.

3.3 Partial equilibrium analysis (PEA)

Method

Partial equilibrium models describe the outcome of a market or a set of markets by depicting the behavioral relations that underlie the outcome. This means that the impact of a change in for instance environmental policy, can be tracked down to its effects on consumption and production decisions. Since the decision rules are explicitly modeled, price effects and substitution effects of a given policy can be analyzed. The results of PEA depend heavily on the assumption that all actors on markets maximize their pay-off by equating marginal benefits and marginal costs, and the assumption that all markets are cleared (see Cropper and Oates (1992) for a survey of economic equilibrium models of environmental problems, and Baumol and Oates (1988) for a classic introduction in this field). The working of partial equilibrium models is best shown by use of the example of section 3.

Application

To keep the model tractable we strip the example from all sectors that are only indirectly accountable for the pollution. Moreover, we focus on lead pollution, so the environmental damage from dumping of plastics is neglected. This means that the oil producing sector is not included in the PE model. This does not change the results of the model, since the oil price is assumed to be determined on the world market. Simplifications like these are typical for PEA, and indeed for any model of economic equilibrium. While for instance MFA aims at completeness, PEA focuses on the elements of the problem that are thought to be essential, neglecting economic relations that are less important. Given the simplifying assumptions we construct a partial equilibrium model describing the example of Section 3. The economic interpretation of Figure 1 and Table 1 is that they describe the *ex post* results of

economic decisions of all actors. Since the model describes the *ex ante* or intended levels of activity, we denote the *ex ante* level of flow f_i by x_i . Or, to put it differently, the economic interpretation of a flow f_i is that it is the equilibrium value of the associated variable x_i . Similarly, p_i denotes the price of a unit of f_i .

In the example transfers take place on five different markets: a market for lead (both new and recycled), for oil, for plastics, and a domestic and a foreign battery market. The model presented below accounts for four markets, because we exclude the oil market. We assume that the raw and intermediate material markets (for lead and plastics) are international markets characterized by perfect competition. This implies that the prices of lead and plastics are determined on the world market. On the market of batteries firms do have some monopolistic leverage, so they can to a certain extent determine the prices of their output. The functional form of the model is described below.

Lead battery production and consumption

Ignoring the plastic casings, the inputs in the production of lead battery are new lead and recycled lead. The production function reads:

$$(x_2 + x_3) = \mathbf{g}(x_1 + x_6)^a, \quad \mathbf{g} > 0, \quad 0 < \mathbf{a} < 1, \quad (1)$$

which describes a decreasing returns to scale technology (*i.e.* the average amount of lead required to produce one lead battery rises with the level of production). Equation (1) implies that new lead and recycled lead are perfect substitutes. Therefore, demand for each input is infinitely elastic, so for non-zero x_1 and x_6 the market price of new lead and recycled lead are identical:

$$p_1 = p_6. \quad (2)$$

The inverse domestic demand function for lead battery is given by

$$p_2 = \mathbf{b}(x_2)^m (x_{12})^s, \quad \mathbf{b} > 0, \quad -1 < \mathbf{m} < 0, \quad -1 < \mathbf{s} < 0, \quad \mathbf{m} < \mathbf{s} \quad (3)$$

For simplicity, we assume that export of lead batteries is a fixed fraction π of total lead battery production, or

$$x_3 = \mathbf{p}(x_2 + x_3), \quad 0 < \mathbf{p} < 1. \quad (4)$$

green battery production and consumption

Plastic is the single input in production of green batteries, so

$$x_{12} = \mathbf{e}(x_{11})^r, \quad \mathbf{e} > 0, \quad 0 < \mathbf{r} < 1, \quad (5)$$

describes the decreasing returns technology of firms in the green battery producing sector. The inverse demand function for green battery is

$$p_{12} = \mathbf{w}(x_{12})^x (x_2)^s, \quad \mathbf{w} > 0, \quad -1 < \mathbf{x} < 0, \quad \mathbf{x} < \mathbf{s}. \quad (6)$$

The restrictions on \mathbf{r} , \mathbf{m} , and \mathbf{s} in equation (3) and (6) guarantee that lead battery and green battery are (imperfect) substitutes, and that the cross-price elasticity is smaller than the own-price elasticities.

recycling

We assume that pure economic motives play no role in the collection of used lead battery. The collection rate (\mathbf{l}) is therefore exogenously determined:

$$x_4 = \mathbf{l} x_2, \quad 0 \leq \mathbf{l} \leq 1. \quad (7)$$

Lead is recovered from the collected lead batteries using a decreasing returns recycling technology that can be described by an exponential function:

$$x_6 = \mathbf{d} x_4 (1 - e^{-S}), \quad \mathbf{d} > 0, \quad S > 0, \quad (8)$$

where S is the level of recycling activity and δ is the *ex post* lead content of a single lead battery.

Denoting air emissions of lead per lead battery by v , the amount of lead per battery is

$$d = \frac{(1-n)(f_1 + f_6)}{f_2 + f_3}, \quad 0 < n < 1, \quad (9)$$

Due to the decreasing returns production function (1), δ changes with the level of lead battery production.

pollution

In this model five sources of pollution exist. Dumping of used lead batteries (f_5) is given by the difference between used and recovered batteries,

$$f_5 = f_2 - f_4. \quad (10)$$

Dumping of lead by the recycling sector (f_7) is the difference between the lead contained in recovered batteries and the amount of recycled lead,

$$f_7 = \alpha f_4 - f_6. \quad (11)$$

Assuming that lead emissions from lead battery production can (partly) be avoided by implementation of abatement technology, air pollution generated by production of batteries (f_8) is gross air pollution minus abated pollution (B),

$$f_8 = n(f_1 + f_6) - B \quad (12)$$

where the abatement technology is such that for all levels of lead-emission abatement activity (A):

$$B = \gamma A^q \quad (13)$$

The price of A is normalized to unity. Since green batteries are not recovered, dumping of green batteries (f_{13}) is

$$f_{13} = f_{12}, \quad (14)$$

Unintentional lead emissions from green battery production (f_{14}) are given by

$$f_{14} = \phi f_{11}, \quad 0 < \phi < 1, \quad (15)$$

where ϕ is the amount of lead emitted per unit of green battery produced. Note that the description of the pollution flows (equation 10-15) implies that mass balance holds.

calibration

Assuming that all firms maximize profits and all markets are in equilibrium, the model can be explicitly solved for all endogenous variables. The parameters and exogenous prices are chosen such that the initial numerical solution of the model is in accordance with the values in Table 1. These parameter values and prices are shown in Table 12. Note that the values of β and ω , and the values of μ and ξ are the same. This means that for identical prices of lead battery and green battery, demand for each type battery is the same.

Table 12. Parameter Values and Exogenous Prices. Monetary quantities are assumed to be measured in \$.

Coefficient	Meaning	Value	Unit
α	scale parameter for lead battery production	0.3	-
β	scale parameter for lead battery demand	1447.5	\$/kg×(yr/unit) ^{μ+ς}
γ	efficiency of lead battery production	18.9	(units/kg) ^a
d	lead content in lead batteries	5	kg/unit
e	efficiency of green battery production	15.5	units/yr×(yr/kg) [?]
γ	level of abatement activity	0.5	-
γ	fraction of used lead batteries that is collected	0.33	-
μ	inverse demand elasticity of lead batteries w.r.t. their price	-0.5	-
γ	fraction of lead that is emitted in lead battery production	0.025	-

?	inverse demand elasticity of green batteries w.r.t. their price	-0.5	-
p	fraction of produced lead batteries for export	0.23	-
?	scale parameter for green battery production	0.3	-
s	inverse cross demand elasticity of green and lead batteries	-0.25	-
f	fraction of substance that is emitted in green battery production	0.0011	-
?	scale parameter for lead battery recycling	1	-
?	scale parameter for green battery demand	49.9	\$/kg×(yr/unit) ^{2+s}
p ₁	price of virgin lead	1	\$/kg
p ₆	price of recycled lead	1	\$/kg
S	level of recycling activity	1.6	-

Policy Experiments

The model of the previous section is used to analyze the policy options for attaining the three environmental goals (*i.e.* reduction of the use of new lead, reduction of air pollution and reduction of waste dumping) that were discussed in section 2. Since the general conclusion in economic theory is that in most cases the most efficient mode of environmental policy is one that uses taxes to change the behavior of agents, we will mainly focus on tax instruments. Hence, the measurement packages of the MFA of Section 3.1 have to be altered. The packages we consider in this section are:

- (i) reduction of resource depletion by taxing virgin lead and by subsidizing green batteries
- (ii) abatement of air pollution by taxing emissions
- (iii) reduction of landfill by promoting lead battery collection and subsidizing recycling.

Table 13. Results of the simulation with PEA

Flow	Name	Initial							Unit
			(i) 100% tax on new lead ($t_1=1$)	(ii) tax on air emissions ($t_8=9.5$)	(iiia) 100% collection ($\lambda=1$)	(iiib) full subsidy on recycling, ($t_6=-1$)	(iiic) subsidy on green battery ($t_{12}=-1$)		
f_1	mined lead ore	800	359	633	300	750	598	kg/yr	
-	landfilled lead	550.5	245.0	439.0	50.6	500.6	433.4	kg/yr	
-	air emission of lead	25.06	11.06	0.46	25.06	25.06	20.22	kg/yr	
p_2	price of lead batteries	44	50	46	44	44	36	\$/unit	
p_{12}	price of green batteries	59	62	59	59	59	703	\$/unit	

The results of the policy experiments are shown in Table 13. The second column of the table shows the results of the baseline simulations, *i.e.* before any environmental policy is implemented. Notice that the figures are identical to the values of the example (Table 13), except for f_7 that is a bit lower than in Table 1. The reason for this differential is that in the PE model simulation we ignore the plastic casings

of lead batteries. For the same reason the flow from the plastic industry into the lead battery industry (f_{10}) is absent in Table 13.

Package (i): taxing virgin lead and subsidizing green batteries

The most straightforward way to reduce the input of new lead is by levying a tax on its use by lead battery producers. The third column of Table 1 reports the results of an *ad valorem* tax (t_1) on new lead that raises the domestic price of new lead by 100%. The results show that the tax reduces the use of new lead in the lead battery sector by more than 50% (f_1 decreases from 800 kg to 359 kg). This reduction has two reasons. First, the increase of the price of lead raises the production costs in the lead battery sector. The higher costs are passed through in the price of lead batteries, so the sales of lead batteries drop (from 150 to 117). Only a small fraction of this reduction is due to substitution towards green batteries (f_{12} rises from 50 to 51). The rest of the drop in sales is caused by substitution away from batteries altogether. Second, the amount of lead used per lead battery falls, due to the decreasing returns assumption in equation (1). Notice that the tax on new lead does not encourage the use of recycled lead, since the share of recycled lead in the total amount of lead used in production of lead batteries drops from 0.2 to 0.18. This on first sight peculiar result has two reasons. First, since a fixed fraction of the lead batteries are collected, the decrease of the lead battery sales lowers the number of collected lead batteries. Second, each of the collected lead batteries has a lower lead content, due to the decreasing returns assumption. This means that it is more costly to recover lead. It should be noted, however, that reduction of the amount of recycled lead is not a robust result. A different choice of (*i.e.* a lower β , and a higher α) could reverse this result.

While the main purpose of the tax is to reduce the use of new lead, the tax is also beneficial for the other environmental objectives of the example. Since both the number of lead batteries and the lead content of each lead battery is reduced, the total amount of dumped lead (f_5 and f_7) is reduced from 550.5 kg to 245.0 kg. The total lead emissions to the atmosphere is also reduced, from 25.1 to 11.1.

Another policy option for reducing the lead depletion is introduction of a subsidy on consumption of green batteries. The last column of Table 13 presents the effects of an *ad valorem* subsidy ($-t_{12}$) of 95%. The subsidy has only a small impact on lead pollution. While the consumption of green batteries rises considerably ($f_{11}=145$), sales of lead batteries drop only marginally ($f_2=137$). This means that the main effect of the subsidy is that it attracts new demand. The reason for the modest success of green battery subsidies is that in the present model consumers perceive lead batteries and green batteries as poor substitutes. For different parameter values (especially a lower σ) the effectiveness of the subsidy could be higher. The impact of the subsidy is also mitigated by a large increase of the price of green batteries (p_{12} rises from 59 to 703). This shows that a large part of the subsidy goes to higher profits for the green battery producing firms.

Package (ii): taxing air emissions

The fourth column of Table 13 reports the results of the introduction of a tax on air emissions of lead (t_8). The tax is a specific tax (levied per kg lead emitted), and is only charged in the lead battery producing sector (so f_{14} is untaxed). The table shows that an emission tax of 9.5 per kg lead reduces air emissions from lead battery production sector from 25 kg to 0.4 kg. The reduction has two reasons. First, the tax raises the costs of production, which raises the price of lead battery and reduces lead battery sales. Second, firms in the lead battery producing sector invest in emission abatement activities in order to lower their tax bill. Given the tax of 9.5 per kg lead, the firms spend a total of 90.25 on abatement. A side effect of the tax is that the lead emission from green battery production are (marginally) increased (by 0.001 kg). Responsible for this is the increase in the price of lead batteries, which raises the demand for green batteries. The net effect of the tax is of course a reduction of total air emissions. The emission tax also reduces lead dumping, since lead battery sales decrease and the

average amount of lead per battery drops. For the same reasons, the use of new lead (and of recycled lead) falls.

Package (iii): promoting collection of used lead batteries and subsidizing recycling

A popular policy for reducing waste dumping is promotion of recycling. In our model there are two ways to raise recycling: by increasing the collection of lead batteries and by raising the amount of lead recovered from collected lead batteries. The impact of both policies are reported in column 5 and 6 of Table 13. Since the collection rate λ is assumed to be exogenously determined in our model, tax instruments can not be used to promote collection of used lead batteries. Instead, we assume that by for instance public promotion campaigns, the government is able to influence λ . Column 5 shows the effects of a very successful campaign that raises the collection rate to 100%. Since this policy prevents dumping of used lead batteries, it solves part of the waste problem ($f_5 = 0$). Dumping of lead by the recycling sector, however, is unchanged ($f_7 = 50$ kg). This seems an odd result, because both the number of collected batteries and the total amount of recycled lead increases, so one would expect either an increase or decrease of dumping of lead by the recycling sector. It can be shown, however, that the constancy of f_7 when λ changes is implicit in the specification of the model, especially in the exponential function for recycling (7)

Raising the collection rate also proves to be a particularly efficient way to reduce the use of new lead (f_1 drops to 300 kg). The reason is that an increase of λ does not affect the number of lead batteries sold. This means that the amount of lead batteries available for collection does not decrease (as it did in the case of a tax on new lead), and recycled lead can function as a substitute for new lead.

Another policy for waste reduction is promotion of recycling. Column 6 reports the outcome of a subsidy ($-t_6$) that reduces recycling costs to zero. As a consequence, the lead in collected lead batteries is completely recycled, so dumping by the recycling sector is avoided. Dumping of used batteries, however, does not change, since the collection rate is unchanged. Therefore, subsidizing recycling cannot lower lead dumping beyond 500.6 kg. The price of lead batteries is unchanged, as are sales of lead batteries and green batteries and air emissions.

Discussion

The advantages and drawbacks of partial equilibrium modeling can be summarized as follows:

1. Economic equilibrium models describe the impact of prices on economic behavior, which allows for the analysis of price-based environmental policy.
2. These models can reveal the complexity of economic relations, and the interdependence of the economic actors. These are factors that determine the effects of policy in a way that is difficult to foresee without such a model.
3. For this type of modeling, a huge amount of information required to formulate a model that mimics real-world mechanisms in a satisfying manner. Not only does one need to estimate the parameters of the model, it is also required to assess the functional form of the relations. This poses severe restrictions to the system's size.
4. The need to keep the model mathematically tractable is an important constraint on the functional form of the equations of the model, often necessitating implausible assumptions.

3.4 Comparison of the results of the three models

In the above, the three models have been applied separately. In this section, we put the results of the three models together in order to spot similarities, differences and possible inconsistencies in the ways these models address the generation and evaluation of options to solve the problem in the example system. Table 14 gives an overview of the results for the three models.

If we regard the options for *reducing the virgin input of lead*, we see that the SFA and LCA model zoom in on the technical solutions. Both generate the option of substitution of lead batteries by green

batteries. The PEA model addresses not technical measures but (economic) instruments: a tax on virgin lead, and a subsidy on green batteries are introduced. Here we see not so much a contradiction, but a different level of entrance into the realm of problem solving options.

Looking at the results we see that the SFA results can be compared quite well with the PEA results. SFA tells us that substitution, if implemented to an extreme degree, is very effective in solving the depletion problem. It also solves the waste and the emissions problem. The PEA options can be regarded as instruments to implement such a substitution. The effectiveness of both options is of course less and is somewhere in between the baseline and the extreme SFA package (ib); we also see that in this case the tax on virgin lead is more effective than the subsidy on green batteries. The question of what happens to the lead battery production sector is addressed differently, exogenously and inadequately in both models. The SFA model regards two extremes, which influences the results quite substantially: only in the drastic package (ib) the problem is solved, in package (ia) it even increases. The PEA model assumes foreign demand to be influenced in the same way as domestic demand. The LCA result is the comparison between green batteries and lead batteries and tells us that these green batteries are indeed preferable from an environmental point of view. A substitution would cause a shift from lead depletion and emissions to oil depletion and hydrocarbon emissions, but with the chosen weighting factors the net result still is beneficial, i.e. causes a lower total score. The comparability with the other two models is less, but the information is relevant for the substitution question and is additional to what the other models provide.

The second option is the *reduction of air emissions*. SFA assesses this option by assuming 99% effective filters in place, and PEA by introducing an emission tax, which again can be viewed as a policy instrument used to implement the supposed techniques. SFA and PEA results point in the same direction again, but the PEA model shows that there are some economic consequences of this tax which are ignored in the SFA model: the demand for lead batteries drops slightly, causing also the required virgin input and the landfilled waste to decrease. The LCA model tells us that reducing air emissions influences the score for the lead batteries more than for the green batteries, although the green batteries still are better in comparison.

The third option is to *decrease landfilling of lead containing waste*. Both the SFA and the PEA model aim to do this by boosting collection and recycling, SFA by assuming that it happens and PEA by introducing a subsidy on recycling. Here the results differ somewhat. Apart from the fact that this subsidy apparently is not very effective in increasing recycling, we also see that the effectiveness from the point of view of the landfill problem is virtually zero in the PEA model, while it is quite substantial in the SFA model. This is due to the fact that the subsidy is not assumed to influence collection, only recovery in the PEA model, which is raised to the extreme of 100% in the SFA model. Again the two models appear to be complementary rather than contradictory: SFA tells us that in principle recycling may help considerably to solve the problem, while PEA adds that implementation probably will be problematical. The LCA results supports the SFA conclusion that recycling is beneficial and adds that with a high collection and recycling rate for lead the score even reverses: now the lead batteries are better than the green batteries.

Table 14. Effects of the three packages as calculated by the three models

model	baseline	(i) substitution		(ii) air emission reduction	(iii) recycling
SFA model total flows of lead, steady state mined lead ore (kg/yr)	800	<i>export LBs</i>	<i>close LB prod.</i>	<i>99% emission reduction</i>	<i>100% collection, 90% recycling</i>
		1000	0	775	325

air emissions of lead (kg/yr)	25	25	0.22	0.25	25	
landfill lead (kg/yr)	551	2	2	551	75.5	
PEA model		<i>tax lead</i>	<i>subs GB</i>	<i>tax air emissions</i>	<i>boost collection</i>	<i>subs.re cycling</i>
total flows of lead, steady state						
mined lead ore (kg/yr)	800	359	598	633	300	750
air emissions of lead (kg/yr)	25.06	11.06	20.22	0.46	25.06	25.06
landfill lead (kg/yr)	550.5	245.0	433.4	439.0	50.6	500.6
LCA model emissions/extractions per unit of function	<i>LB</i>	<i>GB</i>	n.a	<i>LB</i>	<i>GB</i>	<i>LB</i>
				<i>99% emiss. red.</i>	<i>99% emiss. red.</i>	<i>100% collection 90% rec.</i>
mined lead ore (kg)	82	0		82	0	82
dumped used lead battery (units)	13	0		13	0	0
recycling residual (kg)	6.5	0		6.5	0	6
air emission lead battery production (kg)	2.6	0		0.026	0	2.6
crude oil (kg)	3.9	15		3.9	15	3.9
dumped used green battery (units)	0	20		0	20	0
air emission green battery production (kg)	0	2.2		0	0.022	0
<i>weighted total</i>	<i>914</i>	<i>704</i>		<i>851</i>	<i>700</i>	<i>646</i>
						<i>704</i>

4. Evaluation of models

What do we learn from the application of the three different models to one and the same example? Conclusions can be drawn at various levels. In the first place, it can be concluded that each of the models serves its own purposes and therefore has its own strong points as well as its own limitations. From the application to the example, it appears that the results of the three models are in most cases complementary rather than contradictory. SFA can be used to assess whether certain options, as technical measures, could solve the problem in principle. LCA can be used to assess whether certain technical solutions do not lead to other, also serious environmental problems. PEA can be used to look for the most efficient way of implementation, spotting some routes (tax on air emissions) as surprisingly beneficial and others (increasing recycling) as difficult to implement.

In the second place, it appears that this example is indeed quite small and simple for SFA and LCA, while it is a rather large and complex system for the PE model. SFA and LCA models usually handle much larger systems, even in theoretical applications. SFA mostly operates at a macro-level, encompassing all economic sectors insofar as they handle the substance involved. LCA is primarily a micro-level tool; the LCA system is large because of the inclusion of processes in a detailed manner and the allocation of tiny parts of macro-level sectors such as energy or transport. Large systems are possible because the modeling equations used for LCA and SFA are all simple linear equations, while the PE equations are much more complicated. The physical models appear to aim at completeness and

obtain their added value from quantity. PEA on the other hand, which also operates at the micro-level, aims at a much more careful modeling of a few important mechanisms while ignoring the remainder, thus focusing on quality rather than quantity.

A third conclusion following from the above is that both the physical models and the economic model rather obtain their strength from the observing of mechanisms than from describing “the real world”. The SFA model identifies problem-causing mechanisms based on mass conservation, such as stock-building, creating cycles, poisoning of cycles and connections. The LCA model identifies the main problematical parts of functional chains, options to improve chains, and problem shifting between environmental problems. The PEA model identifies the market mechanisms that can be used most suitably to reach a certain end, such as welfare optimization. All such mechanisms are relevant and interesting to model, although it certainly is difficult to address them all simultaneously in a single formal model. This leads to some considerations regarding the use of these models. A first and rather straightforward recommendation is not to use the models for purposes they were not designed for. This may seem rather trivial, however in practice we may observe this rule to be violated sometimes, such as the use of PEA for estimating the pressure on the environment or the use of SFA to compare materials or the use of LCA to assess large societal changes. Other recommendations, such as stated below, refer to the future development and use of economic-environmental models.

5. Towards Integration

One possible direction for development could be to design a procedure to use such models in combination, thus using the advantages of each while minimizing each others shortcomings. If we stick to the example of heavy metals, one could imagine a procedure as follows:

- first use SFA to identify the metal flows, distinguish the problematical flows, select the main flows to regulate and try out the problem solving potential of some technically defined options;
- then use LCA to evaluate the emerging alternatives (either products, materials or production processes) on their side-effects: shifting to other environmental problems, thus identifying the most appropriate ones to be further studied;
- then use PE to model the markets connected with the selected flows-to-regulate and evaluate the various possible instruments on their environmental as well as economic consequences for each option;
- finally introduce the results for the most promising options out of the PE model once again into the SFA model to identify unexpected problem shifting to other parts of the substance chain.

In this way, all models have their proper sequential place without transgressing beyond their natural boundaries, at the same time supporting the evaluation much more strongly together than each alone could do. Theoretically this may be the easiest way to proceed. In practice, this would imply a close co-operation between disciplines, which may not be easy but could certainly be worthwhile.

Quite a different direction of thinking is to attempt an integration of the modeling principles of the three models, in order to develop one new models that has all the advantages and none of the draw-backs. There are some examples of models wherein economic and physical modeling is integrated already. On the micro-level, Materials-Product Chain Analysis (MPCA) can be mentioned, adding mass balance equations to a modeling of markets rather similar to the PEA model in this article (Kandelaars, 1998). On the macro-level the MARKAL model adds one or two markets to a large input-output-like physical structure (Gielen & Kram, 1997). Such modeling also may be very valuable and might be extended in other directions to create a new class of integrated economic-environmental models. The main danger of progressing in this direction is falling into the trap of trying to design “the ultimate model” which can do everything at the same time. In practice it may well be that by integration some of the specific assets of the specialist models are lost. On the other hand, the already mentioned examples of MPCA and MARKAL can be seen as practical compromises in this vein.

Which of these two routes is the most useful one, and how to proceed on them, cannot be decided on the basis of this exercise. For the moment it would seem useful to try both. It may well be a matter of taste. It may also depend on the specific question that needs answering. Anyhow, a field for research seems to be still wide open for the future.

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