# Material flows and economic models

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## Abstract

*The growing awareness 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 elaborate types of analysis. Since all these types of analysis have their merits and demerit 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 Analysis and Economic Equilibrium Analysis . Instead of a lengthy theoretical discussion of each model, we apply each type of analysis 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. An important conclusion of this exercise is that in many respects the models can be seen as complements, rather than substitutes.*

## 1. Introduction

Many environmental problems can be directly related to flows of substances, materials and products through the economy. Several methods have been developed to study such flows, but these include no description of economic mechanisms (allocation, optimisation, 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 references such as Ayres & Kneese (1969), Leontief (1970), Victor (1972) and Perrings (1987). 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 and pollution, production, consumption and waste treatment, 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 partial 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 this class of partial models (see for instance Kandelaars, 1998). Such overviews usually contain a catalogue of abstract properties, like primary object, main assumptions, etc. We felt that a different approach was needed to provide another perspective: that of showing the consequences of the differences between these models in a hypothetical case study. This paper therefore addresses the issue of integration by comparing the approaches and the results of a case study as can be obtained by three partial models: substance flow analysis (SFA), life cycle assessment (LCA) and partial 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 papers are representative for the typical differences that exist between the various model types. A complete list of models would include general equilibrium models, macro models, economic input-output models. Both general equilibrium and macro models can be viewed as extensions of the partial equilibrium model that is discussed in section 3.3, while 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-supply decisions?
- To what extent are certain policy measures capable of influencing material flows?
- Will any interdependency (and in particular: trade-off) between flows of different materials occur when introducing those policy measures?

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, for instance, about the role of materials in the economy, the rigidity of economic relations, the restrictiveness of physical constraints and the way the economy and the environment interact, that are the basis of each modelling approach, can differ importantly. 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 important insights in the crucial differences and similarities between the models. The result of such an exercise would probably be an enumeration of characteristics from which generalisations 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, while 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.

The structure of the example is depicted in figure 1. This figure 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 modelled. 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. Another important simplification is that in the example materials are the single factor of production. Other factors, such as labour and capital are excluded from the analysis.

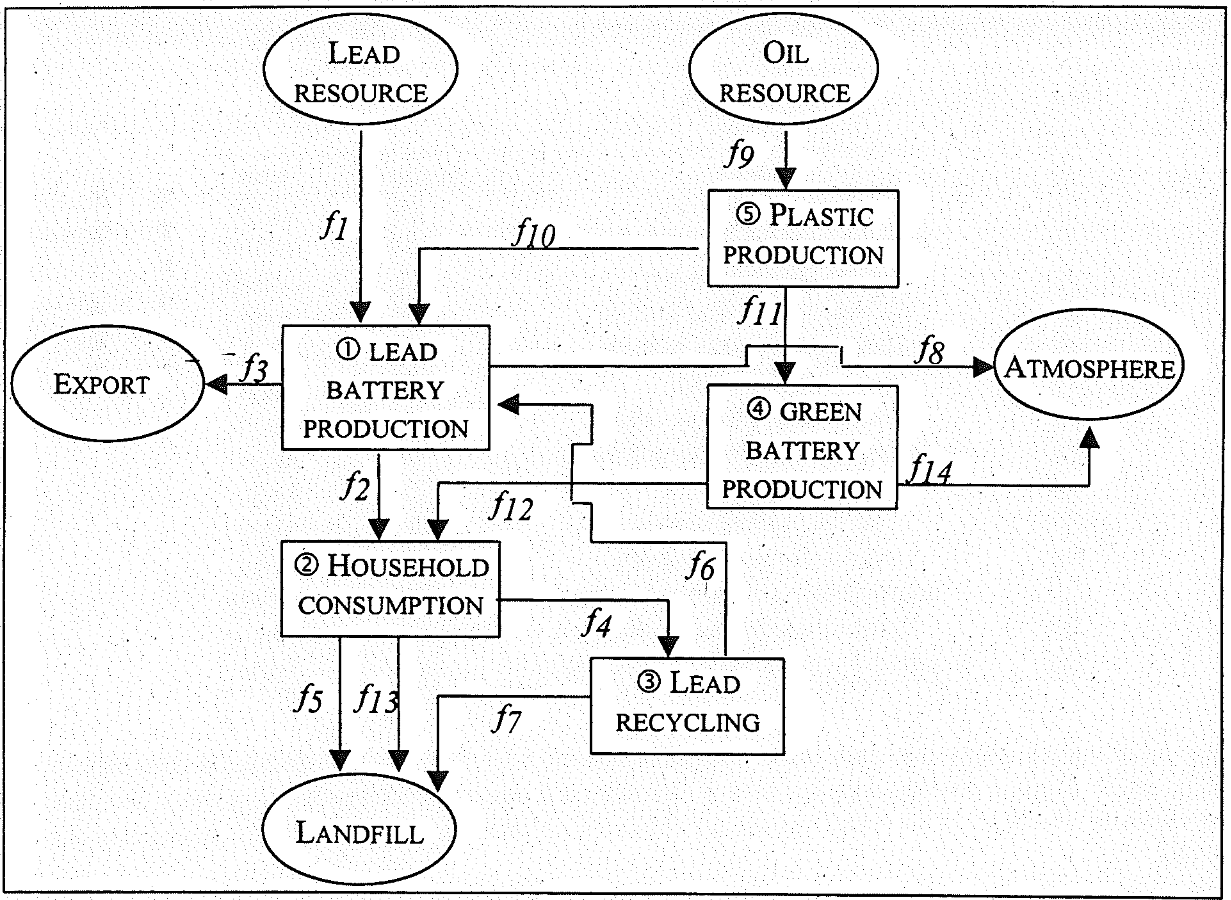


***Figure 1***
*Flow diagram of the battery example: arrows are flows, boxes are processes and ellipses are resources and sinks.*

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 nodes are shown in Table 1. These values are the starting point of the application of each of the models in the next sections. It can be seen that in the initial situation 75% of the batteries are lead battery. 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 in the economy is dumped. Compared to lead dumping, the emissions of lead to the atmosphere are small.

***Table 1** Initial Values of Material Flows*

| # | Name | Quantity | Unit |
|---|---|---|---|
| *f1* | mined lead ore | 800 | kg/yr |
| *f2* | domestically sold lead battery | 150 | units/yr |
| *f3* | exported lead battery | 45 | units/yr |
| *f4* | collected used lead battery | 50 | units/yr |
| *f5* | dumped used lead battery | 100 | units/yr |
| *f6* | recycled lead | 200 | kg/yr |
| *f7* | dumped recycling residual | 55 | kg/yr |
| *f8* | air emissions lead battery production | 25 | kg/yr |
| *f9* | crude oil | 75 | kg/yr |
| *f10* | plastic battery casing | 195 | units/yr |
| *f11* | plastic for green battery | 55.5 | kg/yr |
| *f12* | domestically sold green battery | 50 | units/yr |
| *f13* | dumped used green battery | 50 | units/yr |
| *f14* | 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 flue gasses contain 1% lead. The initial values are chosen such that mass balance holds throughout the example.

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), and waste dumping (by households and by the recycling sector). Congruous to these three problems, we discern three policy objectives for the environmental policy maker: (1) reduction of the use of virgin materials, (2) abatement of emissions to the atmosphere, and (3) reduction of waste dumping. In the next section three different models are employed to analyse the policies for attaining these environmental goals.

## 3. Application of the models

In this section the three selected concrete models for analysing the relationship between economy and environment — MFA/SFA (3.1), LCA (3.2) and PEA (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

For MFA/SFA and LCA, the modelling 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 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 most important flows of money and/or goods within the economic system. It is used as an accounting tool: the mutual deliveries are "measured" and put into 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 behavioural and technical considerations, no attempts are being made to explain the data, or to separate behaviour 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 which in principle 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 modelling, which originates from looking at the economy in a physical sense as described by Ayres (1989) in the concept of industrial metabolism, is rather similar to IOA and therefore is called by some 'environmental input-output analysis' (Schrøder, 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). An important part of such dynamic models is the presence and the development of stocks. 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 exponentially 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 modelling. 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 case 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:

- 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.
- 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.
- 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 Figure 1 are then translated into IO-like equations. The $y$-variables represent the amount of lead connected with the $f$-flows. The set of equations contains exogenously fixed variables of the type $y_1 = a$, dependency equations of the type $y_2 = b * y_1$ , and balancing equations such as $y_3 = y_2 - y_1$ . Exogenously determined variables are the demand for lead batteries ($y_2$), the 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.

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

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 ($y_{13}$):

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

This set is completed by so-called balancing equations to calculate the remaining lead flows, at the same time forcing 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 at an equilibrium and consequently there is no stock change. In this respect the example is shortcoming: signalling and modelling stock changes is an important part of SFA. The choice was made however to confine ourselves to static modelling. 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.

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

***Table 2*** *Variables and Coefficients*

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

**(0.8 of lead in batteries, lead from plastic casing is not recovered)*

Solving this set of equations leads to a result that is identical to 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. Measure package ia leaves the production of batteries intact and channels this production directly to foreign countries. Measure package ib closes down the battery industry completely. This leads to the following changes in the variables and coefficients:

| affected variable | initial value | value package ia | value package ib |
|---|---|---|---|
| f | 150 | 0 | 0 |
| h | 195 | 195 | 0 |
| g | 50 | 200 | 200 |

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%.

| affected variable | initial value | value package ii |
|---|---|---|
| i | 0.025 | 0.00025 |
| j | 0.0991 | 0.000991 |

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:

| affected variable | initial value | value package ii |
|---|---|---|
| k | 0.333 | 1 |
| l | 0.7998 | 0.8998 |

The result of these measure packages for the identified problem flows is summarised and compared with the present situation in Table 3.

***Table 3** Results SFA Model*

| | baseline | ia | ib | ii | iii |
|---|---|---|---|---|---|
| required virgin lead (kg/y) | 800 | 1000 | 0 | 775 | 325 |
| emissions of lead to atmosphere (kg/y) | 25 | 25 | 0.22 | 0.25 | 25 |
| landfill lead (kg/y) | 551 | 2 | 2 | 551 | 75.5 |

Table 3 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, wherein the battery industry has closed down, 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 only the emission from the plastics industry is left. Only 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 usefulness 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 here 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. 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 strong points and limitations of the SFA approach.

1. With SFA, environmental problems can be related to their economic origins, thereby offering possibilities for the identification of potential solutions in a physical/technical sense.
2. SFA is a powerful tool to assess, very quickly and easily, 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 results above 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 SFA purposes, since only then the advantages of the origins analysis and problem shifting to other parts of the chain will show.

4. SFA turns a blind eye for 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 turns a blind eye for shifting of problems outside the substance chain; in the example the problems related to the oil/plastics chain. The environmental consequences of substitution therefore cannot be evaluated.

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 is a tool to assess the environmental consequences of a product from the cradle to the 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 (*e.g.*, 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 standardised: an ISO-standard is under construction, but it will concentrate on procedural matters and main lines of approach, neglecting technical details like formulas.

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 number (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 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 "$CuSO_4$", "$CuCl_2$", etc.).

A final remark is that one cannot make an LCA for a metal. 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 sulphur, carbon and may 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 most often normalised 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 have to be reordered into economic flows (which flow from or to other processes) and environmental flows (which flow from or to the environment).
- multiple processes (*e.g.* joint production, waste treatment including recycling), must be split into independent single processes; this applies to processes 3 and 5 where so-called allocation factors $\lambda$ are used to allocate the recycling residual over treatment of collected used LB and production of recycled lead and allocation factors $\mu$ are used to allocate the crude oil over production of plastic LB casing and production of plastic for GB;
- the consumption process is separated into consumption of LB and consumption of GB;
- the function of the consumption processes needs to be specified; this enters the table as a flow $g_1$ and $g_2$.

This leads to the following process table.

*Table 4 Table of Process Data for LCA*

| flow | ① | ②a | ②b | ③a | ③b | ④ | ⑤a | ⑤b |
|---|---|---|---|---|---|---|---|---|
| total sold lead battery | $f_2+f_3$ | $-f_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| collected used lead battery | 0 | $f_4$ | 0 | $-f_4$ | 0 | 0 | 0 | 0 |
| kg recycled lead | $-f_6$ | 0 | 0 | 0 | $f_6$ | 0 | 0 | 0 |
| plastic lead battery casing | $-f_{10}$ | 0 | 0 | 0 | 0 | 0 | $f_{10}$ | 0 |
| kg plastic | 0 | 0 | 0 | 0 | 0 | $-f_{11}$ | 0 | $f_{11}$ |
| total sold green battery | 0 | 0 | $-f_{12}$ | 0 | 0 | $f_{12}$ | 0 | 0 |
| yr lead battery use | 0 | $g_1$ | 0 | 0 | 0 | 0 | 0 | 0 |
| yr green battery use | 0 | 0 | $g_2$ | 0 | 0 | 0 | 0 | 0 |
| kg lead ore | $-f_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| dumped used lead battery | 0 | $f_5$ | 0 | 0 | 0 | 0 | 0 | 0 |
| kg recycling residual | 0 | 0 | 0 | $\lambda f_7$ | $(1-\lambda)f_7$ | 0 | 0 | 0 |
| kg air emission lead battery production | $f_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| kg crude oil | 0 | 0 | 0 | 0 | 0 | 0 | $-\mu f_9$ | $-(1-\mu)f_9$ |
| dumped used green battery | 0 | 0 | $f_{13}$ | 0 | 0 | 0 | 0 | 0 |
| kg air emission green battery production | 0 | 0 | 0 | 0 | 0 | $f_{14}$ | 0 | 0 |

The table, with numbers inserted, can be seen as two matrices: a matrix **A** that represents the economic flows (8 rows and 8 columns) and a matrix **B** that represent the environmental flows (7 rows and 8 columns). We choose the allocation factors according to Table 5.

*Table 5 Choice of Parameters in LCA*

| parameter | meaning | value |
|---|---|---|
| $\lambda$ | for allocation of process ③ into independent processes ③a and ③b | 0.5 |
| $\mu$ | for allocation of process ⑤ into independent processes ⑤a and ⑤b | 0.5 |

The allocated process data from Table 5 now transform into the two matrices **A** and **B**:

$$\mathbf{A} = \begin{pmatrix} 195 & -150 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 50 & 0 & -50 & 0 & 0 & 0 & 0 \\ -200 & 0 & 0 & 0 & 200 & 0 & 0 & 0 \\ -195 & 0 & 0 & 0 & 0 & 0 & 195 & 0 \\ 0 & 0 & 0 & 0 & 0 & -55.5 & 0 & 55.5 \\ 0 & 0 & -50 & 0 & 0 & 50 & 0 & 0 \\ 0 & 750 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 250 & 0 & 0 & 0 & 0 & 0 \end{pmatrix};$$

$$\mathbf{B} = \begin{pmatrix} -800 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 27.5 & 27.5 & 0 & 0 & 0 \\ 25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 37.5 & 37.5 \\ 0 & 0 & -50 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 5.5 & 0 & 0 \end{pmatrix}$$

Next, the equation $\mathbf{b} = \mathbf{B} \cdot \mathbf{A}^{-1} \cdot \mathbf{a}$ provides the standard calculation procedure for the vector of environmental flows (**b**) that is associated with the vector of product functions (**a**). For this, we choose the two vectors $\mathbf{a}_{LB}$ and $\mathbf{a}_{GB}$ with a functional unit of 100 years of battery use:

$$\mathbf{a}_{LB} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \\ 0 \end{pmatrix}; \mathbf{a}_{BG} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \end{pmatrix}$$

This yields the following tabulated results for $\mathbf{b}(\mathbf{a}_{LB})$ and $\mathbf{b}(\mathbf{a}_{GB})$ respectively:

***Table 6** Environmental Flows according to LCA*

| flow | 100 yr LB use | 100 yr GB use |
|---|---|---|
| kg lead ore | -82 | 0 |
| dumped used LB | 13 | 0 |
| kg recycling residual | 6.5 | 0 |
| kg air emission LB production | 2.6 | 0 |
| kg crude oil | -3.9 | -15 |
| dumped used GB | 0 | 20 |
| kg air emission GB production | 0 | 2.2 |

Furthermore, we will be assuming that a weighting between different pollutants and resources has been set, involving weighting factors as in Table 7.

***Table 7** Weighting Factors and Weighted Results for the LCA*

| flow | weighting factor | 100 yr LB use | 100 yr GB use |
|---|---|---|---|
| kg lead ore | (-)5 | 410 | 0 |
| dumped used LB | 20 | 267 | 0 |
| kg recylcing residual | 3 | 19 | 0 |
| kg air emission LB production | 25 | 64 | 0 |
| kg crude oil | (-)40 | 154 | 600 |
| dumped used GB | 5 | 0 | 100 |
| kg air emission GB production | 2 | 0 | 4 |
| Weighted total | 100 | 914 | 704 |

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

The hypothetical measures that were formulated in the previous subsection have been analysed 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. (Recall that advantages or disadvantages that are related to scale are outside the linear homogeneous formalism, and hence outside the scope of LCA.) 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 LB production ($f_8$) and GB production ($f_{14}$) 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 $\mathbf{A}_{22}$ from 50 to 150, $\mathbf{B}_{22}$ from 100 to 0, $\mathbf{A}_{35}$ from 200 to 229.5, and $\mathbf{B}_{34}$ and $\mathbf{B}_{35}$ from 27.5 to 12.25. 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 GB, there is of course no difference.

*Table 8 Summary of Calculations of Measures that Could Be Considered to Improve Batteries*

| scenario | baseline | | measure ii | | measure iii | |
|---|---|---|---|---|---|---|
| flow | GB | LB | BG | LB | GB | LB |
| kg lead ore | -82 | 0 | -82 | 0 | -82 | |
| dumped used LB | 13 | 0 | 13 | 0 | 0 | 0 |
| kg recycling residual | 6.5 | 0 | 6.5 | 0 | 6 | 0 |
| kg air emission LB production | 2.6 | 0 | 0.026 | 0 | 2.6 | 0 |
| kg crude oil | -3.9 | -15 | -3.9 | -15 | -3.9 | -15 |
| dumped used GB | 0 | 20 | 0 | 20 | 0 | 20 |
| kg air emission GB production | 0 | 2.2 | 0 | 0.022 | 0 | 2.2 |
| Weighted total | 914 | 704 | 851 | 700 | 646 | 704 |

The interpretation of these results deserves some comments. 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 ③ (lead recycling) was redefined in measure iii, while process ① (lead battery production) was left unchanged. Had we defined measure iii as the increase of production of recycled lead (in favour of recycling residual)_and the increase of use of recycled lead (in favour 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 measure 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 measure 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 systematical account follows:

- 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.
- 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.

### 3.3 Partial equilibrium analysis (PEA)

**Method**

Partial equilibrium models describe the outcome of a market or a set of markets by depicting the behavioural 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 modelled, price effects and substitution effects of a given policy can be analysed. The results of PEA depend heavily on the assumption that all actors on markets maximise their pay-off by equating marginal benefits and marginal costs, and the assumption that all markets are in equilibrium (see Cropper and Oates (1992) for a survey of economic equilibrium models of environmental problems, and Baumol and Oates (1988) for *the* 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. 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 characterised 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:

$$(x_2 + x_3) = \gamma\,(x_1 + x_6)^{\alpha}\,, \quad \gamma > 0\,, \quad 0 < \alpha < 1\,, \tag{1}$$

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:

$$p_1 = p_6\,. \tag{2}$$

The inverse domestic demand function for lead battery is given by

$$p_2 = \beta\,(x_2)^{\mu}\,(x_{12})^{\sigma}\,, \quad \beta > 0\,, \quad -1 < \mu < 0\,, \quad -1 < \sigma < 0\,, \quad \mu < \sigma \tag{3}$$

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

$$x_3 = \pi\,(x_2 + x_3)\,, \quad 0 > \pi > 1\,. \tag{4}$$

*Green battery production and consumption*

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

$$x_{12} = \varepsilon (x_{11})^{\rho}, \quad \varepsilon > 0, \quad 0 < \rho < 1, \tag{5}$$

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

$$p_{12} = \omega (x_{12})^{\xi} (x_2)^{\sigma}, \quad \omega > 0, \quad -1 < \xi < 0, \quad \xi < \sigma. \tag{6}$$

The restrictions on $\xi$, $\mu$, and $\sigma$ 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 ($\lambda$) is therefore exogenously determined:

$$x_4 = \lambda x_2, \quad 0 \geq \lambda \geq 1. \tag{7}$$

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

$$x_6 = \delta x_4 \left(1 - e^{-S}\right), \quad \delta > 0, \quad S > 0, \tag{8}$$

where $S$ is the level of recycling activity and $\delta$ is the *ex post* lead content of a single lead battery. Denoting air emissions of lead per lead battery by $\nu$, the amount of lead per battery is

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

Due to the decreasing returns production function (1), $\delta$ 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,

$$f_5 = f_2 - f_4. \tag{10}$$

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

$$f_7 = \delta f_4 - f_6. \tag{11}$$

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 ($B$),

$$f_8 = \nu(f_1 + f_6) - B \tag{12}$$

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

$$B = \psi A^{\theta} \tag{13}$$

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

$$f_{13} = f_{12}, \tag{14}$$

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

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

where $\phi$ 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 maximise 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 9 below. Note that the values of $\beta$ and $\omega$, and the values of $\mu$ and $\xi$ are the same. This means that for identical prices of lead battery and green battery, demand for each type battery is the same.

***Table 9*** *Parameter Values and Exogenous Prices*

| parameters | | | | exogenous prices | |
|---|---|---|---|---|---|
| $\alpha$ | 0.3 | $\omega$ | 1447.5 | $p_1 = p_6$ | 1 |
| $\beta$ | 1447.5 | $\varepsilon$ | 15.5 | $p_{11}$ | 8.8 |
| $\gamma$ | 18.9 | $\xi$ | -0.5 | r | 49.9 |
| $\mu$ | -0.5 | $\nu$ | 0.025 | | |
| $\sigma$ | -0.25 | $\phi$ | 0.0011 | | |
| $\lambda$ | 0.33 | $\psi$ | 1 | | |
| $\rho$ | 0.3 | $\theta$ | 0.5 | | |
| $\pi$ | 0.23 | | | | |

*Policy Experiments*

The model of the previous section is used to analyse 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 behaviour 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 subsidising green batteries, ii. abatement of air pollution by taxing emissions, and iii. reduction of landfill by promoting lead battery collection and subsidising recycling.
The results of the policy experiments are shown in Table 10. The second column of Table 10 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 10), 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 10.

***Table 10*** *Simulation Results PEA*

| | baseline | 100% tax on new lead ($t_1$=1) | tax on air emissions, $t_8$=9.5 | 100% collection (l=1) | full subsidy on recycling, ($t_6$= -125) | subsidy on green battery, ($t_{12}$=-0.95) |
|---|---|---|---|---|---|---|
| $f_1$ | 800 | 359 | 633 | 300 | 750 | 598 |
| $f_2$ | 150 | 117 | 139 | 150 | 150 | 137 |
| $f_3$ | 45 | 31 | 42 | 45 | 45 | 41 |
| $f_4$ | 50 | 39 | 46 | 150 | 50 | 46 |
| $f_5$ | 100 | 78 | 93 | 0 | 100 | 91 |
| $f_6$ | 200 | 85 | 144 | 700 | 250 | 133 |
| $f_7$ | 50 | 25 | 50 | 50 | 0 | 50 |
| $f_8$ | 25 | 11 | 0.4 | 25 | 25 | 18 |
| $f_{11}$ | 50 | 54 | 51 | 50 | 50 | 145 |
| $f_{12}$ | 50 | 51 | 50 | 50 | 50 | 1743 |
| $f_{13}$ | 0.50 | 0.54 | 0.51 | 0.5 | 0.5 | 17 |
| $f_{14}$ | 0.055 | 0.059 | 0.056 | 0.055 | 0.055 | 1.9 |
| $p_2$ | 44 | 50 | 46 | 44 | 44 | 36 |
| $p_{12}$ | 59 | 62 | 59 | 59 | 59 | 703 |
| total lead dumping | 550.5 | 245.0 | 439.0 | 50.6 | 500.6 | 433.4 |
| total lead air emissions | 25.06 | 11.06 | 0.46 | 25.06 | 25.06 | 20.22 |

*Package i. taxing virgin lead and subsidising 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 10 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 battery, so the sales of lead battery drop (from 150 to 117). Only a small fraction of this reduction is due to substitution towards green battery ($f_{12}$ 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 battery. 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 $\beta$, and a higher $\alpha$) 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 10 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 $\sigma$) 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 10 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). Table 10 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 subsidising 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 10. Since the collection rate $\lambda$ 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 $\lambda$. 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 $\lambda$ changes is implicit in the specification of the model, especially in the exponential function for recycling (7).[1]

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 $\lambda$ 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, subsidising 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

An important advantage of economic equilibrium models is that they describe the impact of prices on economic behaviour, which allows the analysis of price-based environmental policy. Another advantage is that these models can reveal the complexity of economic relations, and interdependence of actors. Factors that affect the results of policy in a way that is difficult to foresee without a model. The main disadvantage of this type of models is probably the 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.

## 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.
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 in its extreme form, is very effective in solving the depletion problem. Apart from that 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.

[1] To show this: $f_7$ is constant if $d\lambda(\delta f_2)=df_6$, where $dz$ denotes the change of variable $z$. Equation (7) implies that the optimal amount of recycled lead is $f_6=\lambda(1-v)(f_1+f_6)-r/p_6$. Taking first differences, and substituting in the condition for constant $f_7$ gives $d\lambda(\delta f_2)=d\lambda(1-v)(f_1+f_6)$, which is always true by definition of $\delta$.

The LCA result is the comparison between green batteries and lead batteries and tells us whether these green batteries are indeed preferable from an environmental point of view. It turns out that a substitution would cause a shift from lead depletion and emissions to oil depletion and hydrocarbon emissions. In all, the results of the three models are not contradictory but complementary.

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. In this case, the PEA model seems to encompass the SFA model and adds to it. The LCA model has no additional value here.

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.

## 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 solutions do not lead to other, also serious environmental problems. PEA can then 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 a very small and simple one for both physical models, 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 modelling 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. The PE model at the other hand, which also operates at the micro-level, aims at a much more careful modelling 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, problem shifting between environmental problems. The PE model identifies the market mechanisms that can be used most suitably to reach a certain end, such as welfare optimisation All such mechanisms are relevant and interesting to model, although it certainly is difficult to model them all at the same time.
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 very often. 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 addition to each other, thus using the strong points of each while catching out each others limitations. If we stick to the example of heavy metals, we 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 shifting to other environmental problems
- 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
- 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 alone. 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 modelling principles of the three models, in order to develop one new models that has all the advantages and none of the draw-backs. In section 6, we have discussed some examples of models wherein economic and physical modelling is integrated already. On the micro-level, the MPC model can be mentioned, adding mass balance equations to a modelling of markets rather similar to the PE model in this article. On the macro-level the MARKAL model adds one or two markets to a large input-output-like physical structure. Such modelling 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. In any case there seems to be a field for research still wide open for the future.

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