On the Necessity to Model all Material Flows

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Summary: It is demonstrated that a realistic modelling of the flows of a certain material requires the modelling of many other flows as well. Generalization of this idea leads to a complete modelling of economic processes, after which the material/substance of interest is highlighted for presentational purposes. This idea also enables the compilation of general applicable databases for MFA/SFA, with extensions to other environmental tools, such as LCA.

Keywords: material flows, process modelling

Introduction

Material flow accounting (MFA), substance flow analysis (SFA) and related types of calculations have in common that they concentrate on the flows of one material or substance in a certain region or nation. Although they sometimes have a somewhat wider scope, *e.g.*, heavy metals, the one-material or one-substance approach will be considered here as the typical situation. Concentrating on one material or substance has certain advantages, with respect to clarity as well as to feasibility. For presentational purposes, there is an obvious advantage in restricting the analysis to one material or substance, although the risk of neglecting problem shifting should be acknowledged. The reduced scope that is achieved by looking at only one material or substance could also be considered to imply an important analytical simplification. After all, there is no apparent need to collect data on materials and substances other than that of concern, nor is there any effort needed to model relationships between all these material or substance flows.

This paper investigates to which extent a reduction of scope to one material or substance leads to a reliable result. A small example will serve to demonstrate that the apparent simplification that is obtained by reducing the scope in the above mentioned way is far from straightforward. Either the modelling is simple with a highly unreliable result. Or the modelling is of a daunting complexity. The third option is to model all material or substance flows, so also those in which there is no interest, and to leave out all flows that are not of interest after the calculations have been made, as a kind of presentational translation.

A simple example

This section describes a simple system for which an SFA is carried out in the traditional way. The analysis and the example are largely based on a previous study that is incorporated in my *Ph.D.*-thesis (Heijungs, 1997). The example will throughout be based on the assumption of linearity: doubling the level of electricity production will increase the emission of CO_2 by a factor 2. Inclusion of the fact that this assumption is in some cases not at all satisfied will not be discussed, although it is conjectured that the line of thinking is in principle valid for non-linear modelling as well.

Suppose that one studies a regional economy with only three sectors: radio production, radio use and waste management, which in this simple example represents the only activity of the consumers. See Figure 1 for a flow chart.

It may be observed that there are connections (flows) of many kinds between the sectors and with the environment: crude oil, electricity, *et cetera*. The flows that are transferred between two economic sectors are termed economic flows. These are music (which goes from the "sector" radio use to the listener, who may be regarded as a consuming sector), new radios, old radios and electricity. Some of the economic flows are imported or exported, *e.g.*, electricity is imported because the electricity producing sector is outside the region of study. There are also flows that are produced or consumed internally and externally, *e.g.*, new radios are partly for the domestic market and partly for export. Similarly, the waste management sector processes domestic old radios as well as imported ones. The flows that go from the environment to an economic sector or, the other way around, from an economic sector to the environment, are termed environmental flows; these are waste and crude oil.

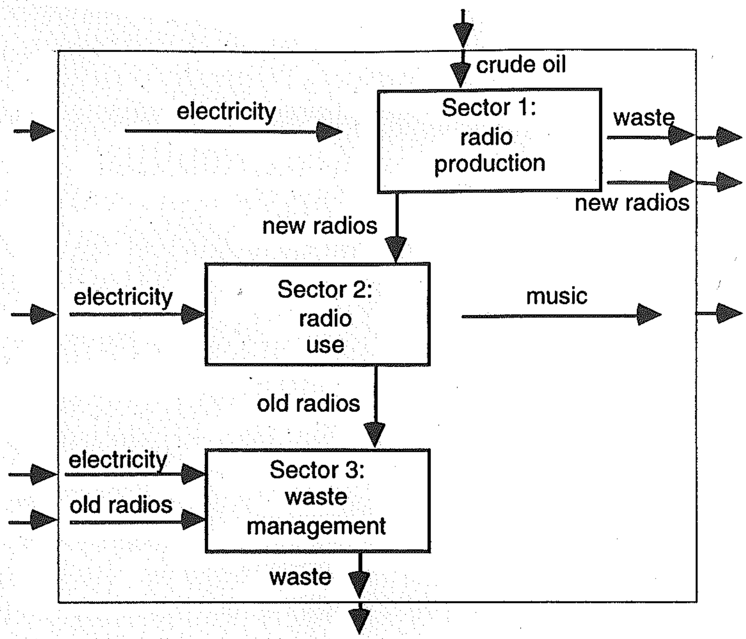

Figure 1: A simple flow chart of a regional economy consisting of three economic sectors, indicated by boxes; the flows are drawn as arrows.

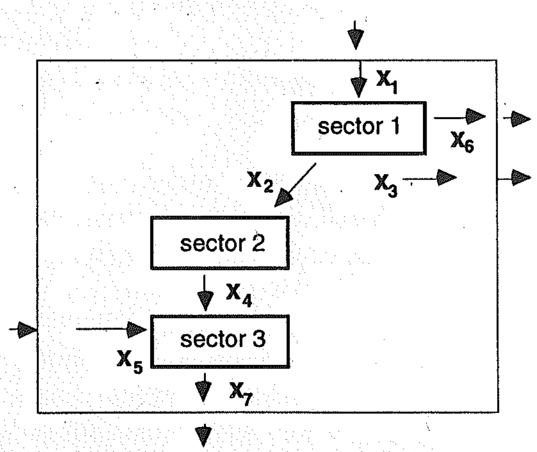

Figure 2: Process tree for the established SFA methodology for the same example as in Figure 1.

Suppose that one wishes to make an SFA with respect to carbon, for example, to analyze the size of the anthropogenic carbon flows that are generated by this regional economy. The usual approach is that the complex economic system is reduced to a system that only exhibits carbon flows; see Figure 2. The carbon-containing flows are denoted by x_1 to x_7.

According to several authors in the field of MFA/SFA, modelling of the interdependency of the flows is to be based on three types of equations.

In the first place, there are balance equations that are based on conservation laws, for each sector one. In this case we have $x_1 = x_2+x_3+x_6$, $x_2 = x_4$ and $x_4+x_5 = x_7$.

In the second place, there are formulas which express certain assumed causal relationships. These formulas often contain one or more coefficients that are determined by matching the measured flows in a base year. In the above example, we could for instance postulate the relationships $x_6 = \alpha(x_2+x_3)$ and $x_3 = \beta x_2$. Assuming that in the base year $x_2 = 2$, $x_3 = 8$ and $x_6 = 20$, we find $\alpha = 2$ and $\beta = 4$.

In the third place, we need one or more fixed parameters to "pivot" the scale of the system. Usually, these fixed parameters relate to a certain level of consumption or import or export. In the example, we could assume that $x_2 = 2$ and $x_5 = 22$ are fixed, not only for the base year, but also in other years.

The total system of equations is therefore as follows:

$$\begin{aligned} x_1 &= x_2 + x_3 + x_6 \\ x_2 &= x_4 \\ x_4 + x_5 &= x_7 \\ x_6 &= 2(x_2 + x_3) \\ x_3 &= 4x_2 \\ x_2 &= 2 \\ x_5 &= 22 \end{aligned} \tag{1}$$

We are left with seven equations in seven variables. Such a system of equations is in general solvable by, e.g., matrix inversion.

A typical use of this modelling could be to introduce a certain policy scenario, e.g., to stimulate people to reduce their radio use by 25%. This translates into changing the fixed parameter $x_2 = 2$ into $x_2 = 1.5$, with consequences for all other flows except x_5.

An extended example

Next suppose that we have expanded the system boundary somewhat, so that the electricity producing sector is included in the new region of study; see Figure 3. Observe that electricity is now exported instead of imported.

The traditional methodology for SFA would proceed as in the previous example. First, the flows that are not within the scope of the study would be erased, and the remaining flows would be numbered x_1 to x_9; see Figure 4.

There are two more flows in the system, and hence two more variables. Consequently, two more equations are required to determine a solution. The first additional equation is easily provided by one more balancing condition: $x_8 = x_9$. The second additional equation poses more difficulties. We have to choose between fixing one of the newly introduced flows and incorporating one or both newly introduced flows in a causal relationship.

An example of the first option is $x_8 = 45$. Clearly, this implies an unrealistic denial of the dependence of electricity generation on radio production, use and treatment.

The more realistic option is the second one, for which one could postulate for instance $x_8 = \gamma(x_2+x_3)+\delta x_2+\varepsilon(x_4+x_5)$ on the grounds that the use of crude oil (to which x_8 is related) for electricity generation depends in a multilinear way on the amount of radios produced (to which x_2+x_3 is related), on the amount of radios used (to which x_2 is related) and on the amount of old radios treated (to which x_4+x_5 is related). This option, although better representing the causal reality, has a number of associated problems. It is quite difficult to find out the exact causal relationship. In the above very simple case, we had already to argue about the assumed dependencies between crude oil and radio production, use and treatment. In a somewhat more involved case, one might easily forget certain "hidden" dependencies. Moreover, the postulated causal relationship requires the assignment of a numeric value to a number of coefficients (γ, δ, ε). This is impossible on the basis of the observed values for the flows x_1 to x_9 in a base year. One would instead have to go into the complete process characteristics, so including the non-carbon containing flows such as electricity.

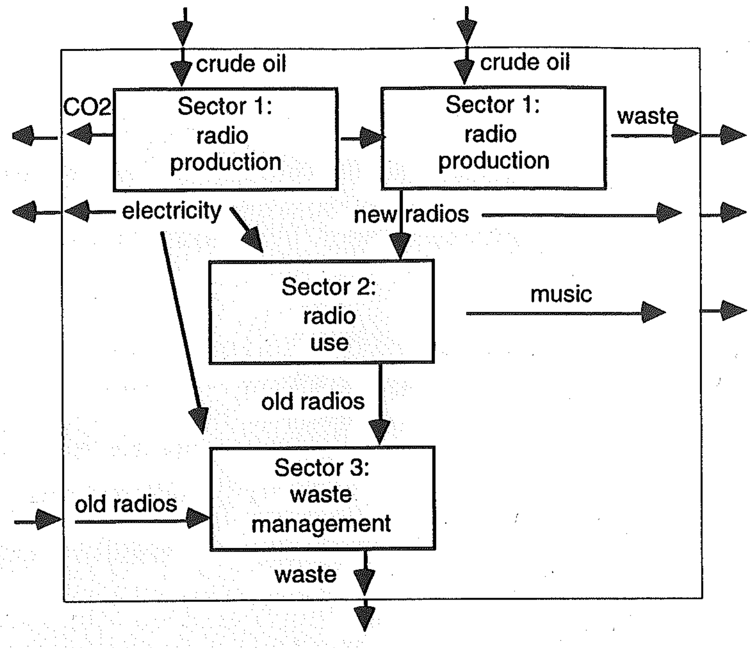

Figure 3: Flow chart of the economy of the larger region, now consisting of four economic sectors.

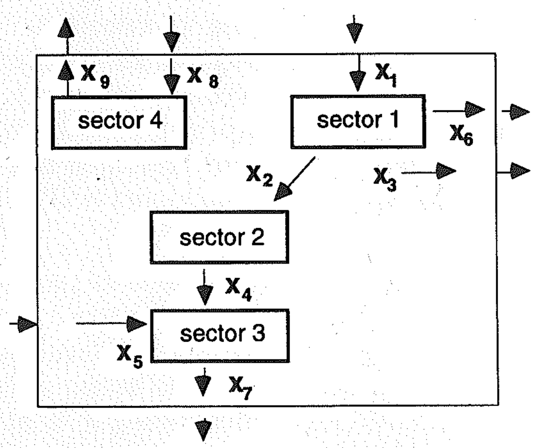

Figure 4: Process tree for the established SFA methodology for the same extended example as in Figure 3.

The extended example revisited

It is proposed that a full accounting of the economic sectors, so not only of the carbon flows, but of all material flows, is the key to easily constructing a consistent MFA or SFA. To illustrate this statement, we will redo the extended example in another way. The complete method extends the confinement of this proceedings. This paper only sketches the procedure. In Heijungs (1997), a formalized matrix procedure is derived.

Each sector is considered to satisfy a linear scaling law. This means that, say, sector 2 may be represented as

$$\begin{pmatrix} y_{crudeoil,1} \\ y_{electricity,1} \\ y_{newradios,1} \\ y_{waste,1} \end{pmatrix} = \begin{pmatrix} z_{crudeoil,1} \\ z_{electricity,1} \\ z_{newradios,1} \\ z_{waste,1} \end{pmatrix} q_1 \tag{2}$$

Here the z's represent the fixed technical coefficients, and the y's represent the flow of each of the materials when the activity level of the sector is q_1.

The flows of carbon are obtained by imposing a "filter" that only transmits the amount of carbon of each flow. Supposing that one new radio contains 1.5 kg carbon, the transmission coefficient for that flow is 1.5 kg C/new radio. Similarly, for electricity it is 0 kg C/MJ electricity.

It is clear that a reduction of radio use by 25% brings about a decrease of the activity level of the radio use sector: $q'_2 = 0.75\ q_2$. This, in turn, brings about a reduction of all flows to and from that sector by 25%. These reduced flows have consequences for the activity levels of sectors 1, 3 and 4 respectively. The reduced activity level of sector 2 has additional consequences for the electricity flow and hence for the activity level of sector 4. A doubly reduced flow of crude oil and CO_2 results, from which the carbon flows can be deduced by the filtering procedure using the transmission coefficients, effectively hiding all non-carbon flows.

Discussion

It has been shown that, without making any assumption on causal relationships, and without calculating any proportionality constant (the above α to ε), the consequences of the policy scenario can be elaborated. This is true not only for the carbon-connected sectors, but also for the non-carbon-connected sectors, like electricity production. All causal relationships have been laid implicitly through a specification of the complete set of transactions: radios, electricity, et cetera. The only vital assumption is that of linear scaling of sectors by means of activity levels. This is an assumption that is very often made, e.g., in input-output analysis (Miller, Blair, 1985), in activity analysis (Koopmans, 1951) and in general equilibrium models (Von Neumann, 1945/1946). It is also made in traditional MFA/SFA modelling; see the first example in which relations like $x_6 = \alpha(x_2+x_3)$ occur.

The above implies that, as long as one sticks to linear models, there is no need to model causal relationships between flows in a system. By introducing very many coefficients in the traditional set-up, one may be able to include all relationships that run via other materials or substances than that of concern. Unfortunately, one can only do so at the price of determining this large number of coefficients. It appears that is a complicated task. More generally, the modelling of the interdependency of substance flows is not easy, as will be clear from expositions like that of Schrøder (1995), Baccini, Bader (1996) and Van der Voet (1996). The present paper enunciates the abolishment of this complex element of MFA/SFA.

The idea has, however, wider consequences. The representation of a sector in terms of technical coefficients of all materials that enter and leave it creates the possibility to construct a database of sectoral data for use in an MFA/SFA of any material/substance. The example could also be elaborated to establish the material/substance flows of sulphur, metals, radios or, even, energy. The only difference is the vector of transmission coefficients. But the data, the method of analysis, and even the bulk of the calculations for a certain region are exactly the same. Energy analysis (Anonymous, 1974) can thus be seen as an MFA/SFA for a non-tangible substance.

An even wider implication is that of harmonization of methods and databases with other tools than MFA/SFA. Heijungs (1997) is concerned with the derivation of the methodology for life cycle assessment (LCA) from the same principles and using the same data as MFA/SFA. Even risk assessment and environmental impact assessment could be regarded as members of the same family, all members having a lot of "genetic" material in common, and all members "feeding" from same resource. This appears to be an important step towards efficient and coherent environmental decision-support.

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