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LINKS BETWEEN THE MICRO AND THE MACRO FLOWS: SUBSTANCE FLOW ANALYSIS

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LINKS BETWEEN THE MICRO AND THE MACRO FLOWS: SUBSTANCE FLOW ANALYSIS*

1. Introduction

Many of the environmental problems we are facing today are a result of society's processing of materials. One of the challenges of economics is to relate the generation of waste and emissions to societal developments. This can be approached from many sides. One possibility is to look at the societal system in environmental terms. This approach is taken by Ayres (e.g. Ayres 1989; Ayres et al.1989; Ayres and Simonis 1994) in his introduction of the concept of industrial metabolism. This concept argues the analogy between the economy and environment on a material level: the economy's "metabolism" in terms of materials mobilisation, use and excretion to create "technomass" is compared to the use of materials in the biosphere to create biomass. Whereas the biosphere has had billions of years to evolve and attune its processes to such a state that waste generated in one process is converted into a resource for another, the economy is still in its early stages of wastefulness. In order to speed up 'economic evolution', society must look to the biosphere for guiding principles. The description of the economy thus is limited to a description of the physical economy. The research area of industrial ecology (e.g. Jelinski et al., 1992; Socolow et al., 1994; Graedel and Allenby, 1995; Ayres and Ayres, 1996; Allenby, 1999) occupies itself among others with elaborating and operationalizing this concept, and takes the physical economy as its primary subject.

An important research principle in this field is the materials balance, (e.g. Kneese et al., 1970; Ayres and Ayres, 1996) a tool for describing the materials regime of the economy based on the Law of Mass Preservation, analogous to the long-standing practice of investigating ecological materials cycles. Analytical tools based on the materials balance are Materials Flow Analysis (MFA) and Substance Flow Analysis (SFA). These tools are useful for supporting environmental policy (Bringezu et al., 1997): they enable policy makers to trace the origins of resource depletion and pollution problems and to evaluate the appropriateness of the societal management of materials and substances.

2. Material Flow Accounting (MFA)

MFA is a widely used technique within environmental science. Studying the material basis of the world's economies can generate valuable insights in the process of formation of environmental hazardous emissions and waste flows and of depletion of natural resources. MFA studies vary in complexity, ranging from a "simple" materials bookkeeping for a certain year to complex dynamic analyses calculating future flows and stocks. Next to that, the aim of the MFA can be very diverse: studies focussing on the metabolism of industrial systems like the metals industry the chlorine industry, pioneered by Robert Ayres, studies focussing on the total or bulk material flows within modern economies (brought into the political arena mainly by the Wuppertal Institute), and studies focussing on the flows of one specific (group of) substance(s) within economy and environment (mainly in Scandinavia, Austria, Switzerland and the Netherlands). However diverse these studies and their aims may be, the techniques which are used within the analyses are similar. The fact that, in the end, inflow equals outflow is the simple central argument in all studies.

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*. This document was prepared by Mr. Rene Kleihn and Ms. Ester van der Voet, Centre of Environmental Science (CML), Leiden University, Netherlands.

3. Bulk-MFA

The type of MFA which is also called *bulk-MFA* ,is characterised by the fact that all material flows are accounted for on a mass basis regardless of their nature. The result of such studies normally consists of a list of inflows and outflows for the studied country, region or city. The material flows are then aggregated on a mass basis into single indicators like DMI and DPO (excluding hidden flows) and TMR and TDO (including hidden flows). These indicators are often used as general indicators for societal metabolism and compared with economic and social indicators like GDP and population.

Material flows generated by human societies are at the heart of many of the most important environmental problems. The material metabolism of societies should thus be an important object of study. In order to get insight in the functioning of the metabolism of societies a complete quantitative overview of flows of materials entering, leaving and accumulating within the system is needed. A bulk-MFA provides such information on the metabolism of societies. The accounts are set up in a systematic manner which make the results comparable between different countries and different moments in time.

The desegregated information which is being collected in bulk-MFA studies provide useful insights in the material basis of human societies. In industrial societies the dominance of water and fossil fuels is vividly illustrated for example. Flows of drinking water dwarf all other material flows which emphasises the excessive need for clean fresh water in those societies. The next largest type of flow are those connected to the use of fossil fuels which indicates our dependence on unsustainable sources of energy.

An important strength of bulk-MFA is the fact that the results can be presented in the form of one aggregated indicator. Because of this the methodology provides a macro-indicator which can be compared with the main macro economic indicator: GDP. Decoupling of economic growth and material flows can thus easily be analysed. However, like GDP, completely aggregated indicators like DMI and DPO clearly have their limitations. A substitution of material intensive processes by processes with emissions of small quantities of toxic compounds for example will result in a decrease in bulk-MFA indicators while actual environmental impacts will most likely increase. Thus bulk-MFA indicators are not always good indicators for environmental pressure since the differences in environmental impacts of the materials are not taken into account. If the focus is on specific environmental problems linked to specific (groups of) substances another type of MFA is needed: Substance Flow Analysis (SFA).

4. Substance Flow Analysis (SFA)

SFA aims to provide relevant information for an overall management strategy with regard to one specific substance or a limited group of substances (van der Voet, 1996). In order to do this, a quantified relationship between the economy and the environment of a geographically demarcated system is established by quantifying the pathways of a substance or group of substances in, out and through that system. In SFA the economy thus is viewed only in terms of flows of a specific (group of) substance(s). The methodology is similar to bulk-MFA but the applications may be different. Mass and bulk flow studies provide macro economic indicators (von Weizsäcker et al. 1997; Adriaanse et al. 1997), while studies on flows of substances can be related to specific environmental problems and thus provide input for a pollutants policy. An example of the aggregated results of an SFA is given in Figure 1.

In general terms, substance flow studies comprise the following three step procedure (van der Voet et al. 1995b): (1) definition of the system, (2) quantification of the overview of stocks and flows, and (3) interpretation of the results. All three steps involve a variety of choices and specifications, each of which depends on the specific goal of the study to be conducted, as will be argued below. The first step in any materials flow study is to define the system. The system must be determined with regard to space, function, time and materials. If necessary, the system can be divided into subsystems. The various categories of processes, stocks and flows belonging to the system must be specified. Finally, this results in a flow chart: the specification of the network of nodes. To define the SFA system, a number of choices must be made with regard to the following aspects: (1) spatial demarcation, (2) functional demarcation, (3) time horizon, and (4) materials to be studied.

4.1 SFA modelling

The quantification of the network is the next step. This involves identifying and collecting the relevant data on the one hand, and modelling on the other. Three possible ways of modelling the system are briefly discussed here, all three types having their own data requirements, as well as their own potential for policy support: (1) accounting or bookkeeping, (2) static modelling, (3) dynamic modelling

Accounting

The first way to ‘model’ the system is to treat it as an accounting system. The input for such a system consists of data regarding the size of the system's flows and stocks of goods and materials, that can be obtained from trade and production statistics, and if necessary also data regarding the content of specific substances in those goods and materials. Emissions and environmental flux or concentration monitoring can be used for the environmental flows. A combination of those data together with application of the mass balancing principle then must lead to the desired overview of flows and stocks.

The accounting overview may also serve as an identification system for missing or inaccurate data. Missing amounts can be estimated by applying the mass balance principle. In this way, inflows and outflows are balanced for every node as well as for the system as a whole, unless accumulation within the system can be proven. This technique is most commonly used in materials flow studies, and can be viewed as a form of descriptive statistics (e.g. Ayres et al. 1988; Olsthoorn 1993; Fleckseder 1992; Palm and Östlund 1996; Tukker et al. 1996, 1997; Kleijn et al. 1997; Hansen and Lassen 2000). There are, however, some examples of case studies that specifically address societal stocks (Bergbäck and Lohm 1997; Bergbäck, Johansson and Molander 2000) and use these as an indicator for possible environmental problems in the future.

Static modelling

In the case of static modelling, the process network is translated into a set of linear equations describing the flows and accumulations as dependent on one another. Emission factors and distribution factors over the various outputs for the economic processes and partition coefficients for the environmental compartments can be used as such variables. A limited amount of accounting data is required as well for a solution of the set of equations, but the modelling outcome is determined largely by the distribution pattern. The description of the system as such a matrix equation opens possibilities for various types of analysis: the existence of solutions, the solution space, and the robustness of the solution can be studied by means of standard algebraic techniques, as is shown by Bauer et al. (1997) and by Heijungs (1994, 1997) for the related product Life Cycle Assessment.

Static modelling can be extended by including a so-called origin-analysis in which the origins of one specific problematical flow can be traced at several levels (van der Voet et al. 1995c; Gleiss et al. 1998). Three levels may be distinguished:

- direct causes, derived directly from the nodes balance (for example, one of the direct causes of the cadmium soil load is atmospheric deposition);
- the economic sectors, or environmental policy target groups, directly responsible for the problem, identified by following the path back from node to node to the point of emission (for example, waste incineration is one of the economic sectors responsible for the cadmium soil load);
- ultimate origins, found by following the path back to the system boundaries (for example, the import of zinc ore is one of the ultimate origins of the cadmium soil load).

Furthermore the effectiveness of abatement measures can be assessed with static modelling.

The result of steady state modelling may be regarded as a caricature of the present management regime. It is therefore most suitable for comparisons between management regimes. Static and steady state models have been proposed by Anderberg et al. (1993) and applied for example by Schrøder (1994), Baccini and Bader (1996), Boelens and Olsthoorn (1998), van der Voet et al. (2000) and also, for purely environmental flows, by Jager and Visser (1994).

Dynamic modelling:

The main difference between static and dynamic SFA models lies in the inclusion of stocks in society (Ford 1999): substances accumulated in stocks of materials and products in households or in the built environment. Until recently, MFA has concentrated mostly on flows. During the past few years, MFA researchers have realised that stocks may be equally or sometimes even more important. One of the environmental issues where stocks play an important role in SFA is in the prediction of future emissions and waste flows of products with a long life span. In some way or another information on the societal stocks of PVC is needed to supply policy makers with information about future outflows: today’s stocks are tomorrow’s emissions and waste flows. In some studies the magnitude of the anthropospheric stocks has even been the primary focus of the study (e.g. Bergbäck & Lohm 1997 and Patel, 1997). These exercises have established the importance of considering stocks. Large stocks have accumulated in the societal system which must be dealt with in some way or other (Brunner & Baccini, 1992; Obernosterer et al., 1998). Future CFC emissions from present (1998) stocks for example are estimated, even assuming a world-wide successful implementation of the Montreal protocol, to roughly equal 75% the total added past emissions (Kleijn & Van der Voet, 1998). Other studies that are dedicated to the analysis of accumulated stocks of metals and other persistent toxics in the societal system are: Gilbert and Feenstra 1992; Bergbäck and Lohm 1997; Baccini and Bader 1996; Fraanje and Verkuijlen 1996; also Lohm et al. 1997; Kleijn, Huele and van der Voet 2000. Such build-ups can serve as an ‘early warning’ signal for future emissions: one day, the stocks may become obsolete or recognisably dangerous (as has happened with asbestos, CFCs, PCBs and mercury in chlor-alkali cells). Then the stocks may be discarded and end up as waste and emissions. In some cases, this delay between inflow and outflow can be very long indeed. Bergbäck and Lohm (1998) also draw attention to stocks of products no longer in use, but not discarded yet: old radios or computers in basements or attics, out-of-use pipes still in the soils, old stocks of chemicals no longer produced such as lead paint or pesticides. They conclude that such “hibernating stocks” could be very large. In order to estimate future emissions, which is a crucial issue if environmental policy makers are to anticipate problems and take timely action, it appears that such stocks cannot be ignored.

When using MFA or SFA models for forecasting, stocks therefore should be a vital part. Flows and stocks interact with each other: stocks grow when the inflows exceed the outflows of a (sub)system and certain outflows of a (sub)system are proportional to the stocks.

For this dynamic model, additional information is needed with regard to the time dimension of the variables: the life span of applications in the economy, the half life of compounds, the retention time in environmental compartments and so forth.

Calculations can be made not only on the 'intrinsic' effectiveness of packages of measures, but also on their anticipated effects in a specific year in the future, and on the time it takes for such measures to become effective. A dynamic model is therefore most suitable for scenario analysis, provided that the required data are available or can be estimated with adequate accuracy

4.2 SFA Indicators

The use of indicators can be great help in the interpretation of the results. SFA indicators can be selected from the overview of flows and stocks, by singling out a specific flow or stock as the relevant one to follow, or they can be calculated directly from the overview. Indicators may be defined for environmental flows and/or stocks, as an addition to the numerous environmental quality indicators already existing. Other possibilities are indicators for economic substance flows, or indicators for integrated chain management, which bear on (possible, future) losses from the economy to the environment; i.e. 'leaks' out of the economic cycle. Examples include materials intensity, economic throughput, the technical or energy efficiency of groups of processes, secondary vs. primary materials use and so on (Ayres 1997a). Another possibility is to compare economic mobilisation of a certain substance with natural mobilisation; as a measure of potential risk (Huele, Kleijn and van der Voet 1993). This goes in the direction of the study of biogeochemical cycles and their transformation by man's activity into anthropo-biogeochemical cycles.

Indicators should be designed to provide information of relevance for an integrated substance chain management policy, for example regarding: (1) the existence and causes of environmental problems related to the substance; (2) the management of the substance chain or cycle in society; (3) early recognition of future problems and (4) the influence of policy measures, including both their effectiveness and various types of problem shifting. In addition, requirements can be defined for the indicators as a group, which must be suitable for evaluating an SFA overview for a specific year but also for evaluating changes in flows and stocks over time as well as alterations thereof, as induced by environmental policy. Therefore, a comparison between different regimes must also be possible. See also Guinée et al.(1999) and Moolenaar et al. (1997) for agricultural soils and systems.

4.3 Studying substance flows in relation to each other

One of the most important aspects of SFA is that the flows of substances are studied in relation with each other. An example of this comes from the study of the flows of chlorine and its compounds through society. Chlorine flows within industrial systems are very much interlinked. A large number of processes within the chlorine industry, including the incineration of chlorinated waste flows, produce hydrochloric acid as a by-product. This hydrochloric acid is often used within the production of PVC, which by some will be regarded as a great example of industrial ecology while others will think of it as just another argument to ban PVC. Because of this link between the production of PVC and the rest of the chlorine chain a ban on PVC will have an enormous impact on the whole chlorine industry: one of it's most important by-products will run into a ”dead-end” and become a major waste flow which would have to lead to a major restructuring of the chlorine industry.

Another example can be found within the realm of metal flows. The use of cadmium in diffuse applications can lead to critical levels in the environment. Emission prevention, and maybe even a ban on certain cadmium containing products therefore seem rational actions for policy makers. However, MFAs have led to the insight that emission prevention and even product bans will not solve the problem. Since inflow always equals outflow the only way to reduce the outflow to the environment is to reduce the inflow to society. Cadmium however, is produced not on demand but as a by-product of the zinc industry. Like when one tries to close the exit of a colony of ants, immediately after closing one exit, another one will be created. The only real solution to this problem is thus to either reduce the amount of zinc being produced or to immobilise the cadmium directly after production. Some have already argued that the production of statues would be a good option.

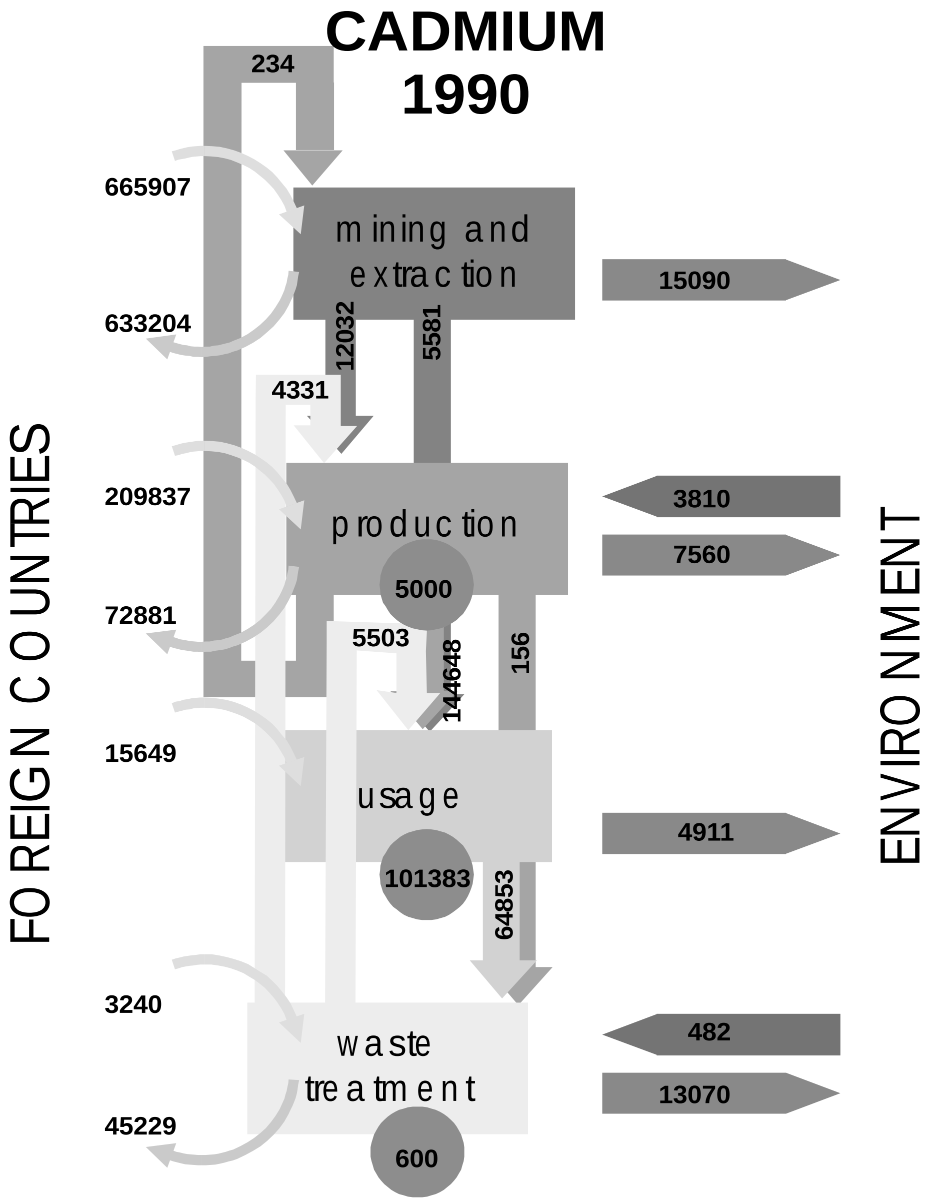
5. Links between bulk-MFA en SFA

As discussed above there are important similarities between bulk-MFA and SFA. The type of accounting and the mathematical techniques which are used are almost identical. The object of study however is different and therefor the applications are different. Where the outcomes of bulk-MFA can be used single indicators of the material basis of societies, SFA can be used to trace back and analyse the substance flows which are related to specific environmental problems. In our view however bulk-MFA and SFA strengthen each other when the are used in combination. The following Links between the two can be thought of:

- with the aid of e.g. mass fractions of substances in products or materials the data generated by the one can be used as an input for the other;
- bulk-MFA is usually focussed on the inflows and outflows of the system while in SFA the focus is on the internal flows in society and the relations between those flows. Physical Input/Output tables may function here as a *traité d'union*;
- one of the most common criticisms on bulk-MFA is that the link between the on mass base aggregated flows of materials and environmental problems is very indirect. This problem is at least partly solved when bulk-MFA is combined with a number of SFAs quantified in kg relevant substance or in environmentally weighted kg;
- in SFA different types of modelling are used to evaluate policy measures and to predict future flows and stocks. The modelling that is used in SFA could be introduced in bulk-MFA;
- SFA and bulk-MFA get very close when flows of bulk materials are studied such as water, steel or paper;

Since a number of important links exist between bulk-MFA and SFA, both tools can benefit from the combining the two. Also in a policy context the use of both tools together will broaden the scope of their possible applications.

Figure 1. **Example of an overview of the results of an SFA-study for cadmium**



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