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1. Introduction and outline

Different types of models have been developed to analyze the physical flows of materials, energy and products. The various methods are not interchangeable, though they are related and show certain similarities. This chapter presents an overview of the models that are commonly used for analyzing physical flows with an emphasis on physical flow modelling applied to environmental problems.

The strengths and weaknesses of the models as well as their similarities and differences are discussed. This will support the selection process of appropriate methods for specific problems.

Methods to study physical flows include materials flow analysis, physical input-output analysis and life-cycle assessment. These methods have different data needs, aggregation levels, purposes and applications. Consequently, the type and quality of results are highly dependent on the chosen method. Besides this description a comparison is made between physical flow models and materials-product (M-P) chain analysis, which combines physical flow with economic modelling.

Here, the term materials flow is interpreted in a broad sense meaning that it covers not only chemical elements, but also substances and compound materials, such as PVC. Materials flows are usually measured in kilograms and energy flows in Joules. The product flow is related to a particular service and measured in functional units.

To be able to evaluate the different methods, model characteristics are compared. Section 2 discusses a number of important characteristics, such as the type of model and temporal aspects. Then, three main methods are separately discussed. Section 3 presents materials flow analysis. A second method discussed in Section 4 is physical input-output analysis. Life cycle assessment is a third methods discussed in Section 5. Section 6 compares the described methods and M-P chain analysis according to the characteristics. An evaluation and discussion is given in Section 7. Section 8. presents the main conclusions.

2. A typology of modelling methods

The real world is, because of its complexity, not directly accessible to the human mind. Modelling is used to catch some of this complexity by focusing on certain aspects of reality. To choose these relevant aspects, the system boundaries, the level of aggregation and the choice of elements and relationships need to be defined. This implies that a certain part of reality can be modelled in multiple, completely different ways, dependent on the goal of the model.

For researchers and policy makers it is important to know which types of model can be chosen to analyze policies and which are the advantages and restrictions of each of them. In addition, other choices need to be made, such as regarding the time horizon, the spatial scale, the level of aggregation, and the units of study in the model adopted. For each of these criteria various options exists, and for each of them a choice needs to be made, preferably in line with the other criteria. The following set of criteria will be used as a guideline for discussing the methods in the following sections.

Type of model

Two types of models are distinguished: descriptive and optimization models. Descriptive models represent the situation on a specific period in time, e.g. a year or a historical description of several years in the past. These models can describe the state of the environment, determine the emissions and waste that have been discharged, or assess the natural resources that are used in a certain period. When based on historical data or time series, these models may be used for forecasting purposes provided that no major changes in the historical trend will take place. In case external variables follow different trends, scenarios may be developed to simulate these trends.

Another type of model are optimization models. These are meant to maximize or minimize according to one single or to multiple objectives. An example of a single objective is to assess the optimal rate of extracting raw materials at a give welfare or demand function. An example of a multiple objective model is an equilibrium model, which is based on two objective functions of which the solutions should be in equilibrium, for example, the profit maximization of producers and the utility maximization of consumers. This results in demand and supply functions. Market prices clear markets. In this example, the two objective functions in the system interact to obtain an equilibrium.

Optimization models can be used to determine the effects of a certain policy or another change on the variables in the model. Optimization models may be based on historical data or time series.

Aggregation of the model

For modelling a certain system a level of aggregation has to be chosen. Within the order of decreasing aggregation the following levels can be discerned: macro, meso and micro level.

(i) Macro level (region, country); models on a macro level are, for instance, national energy and materials use and environmental degradation.

(ii) Meso level (product chain, sector); meso models may be used for investigating the interactions between industrial sectors and for describing product life cycles. The flow of materials and energy between the objects of study, e.g. industrial sectors, is described here. This enables analysis of the effects of changes in one sector with on other sectors.

(iii) Micro level (product or firm); micro models are characterized by a still lower level of aggregation. Here a firm, product or production system is analyzed.

Orientation of the models

For physical flow modelling the orientation may be on economic, physical, or environmental aspects.

(i) Models with an economic orientation focus on functional flows, monetary units or other economic variables. These models are widely applied and, on a highly aggregated level, may cover rather large systems, like geographical regions or branches of industry (macro-economic). Standard input-output models are usually based on the above mentioned viewpoints. On a less aggregated level, the models are related to specific organizations, production processes or products (micro-economic).

(ii) Physically or technically oriented models describe materials and energy flows, like raw materials, products and waste. In such models, quantities are expressed in physical (SI-) units, like kg and Mjoule. The physical flows may be measured on both as inputs or outputs.

(iii) Models with an environmental orientation are usually based on physical models and focus on depletion and discharge of materials and energy. Strictly speaking, the environmental orientation may be seen as a part of the physical orientation. Here, it is taken separately because the focus may be on other units than kilograms and Mjoules. This orientation may account for (eco)-toxicity and other harmful effects, such as acidification and global warming potential.

Another classification of the orientation of a model is the unit that is examined. For the analysis of physical flows a material, a process, a product or a service may be examined.

(i) Materials oriented studies focus on specific materials for which the flow is described and for which alternatives and effects of policies may be analyzed.

(ii) Process oriented research investigates either alternative options for certain processes or improvement of existing processes.

(iii) Product oriented studies focus on a specific product. The materials and energy flows that are related to a product life-cycle are described in relation with, for example, technological innovations. Products are measured in functional units, or in case of a discrete product the product itself.

(iv) A service oriented approach focuses on the desired function of the product, for instance, the transportation of x tons over y km. This approach takes the service offered by a product as the basic criterion, rather than the product itself that is designed to provide this service. Substitution between different products that all are designed to provide similar services is the basic mechanism that is studied. Services are expressed in functional units enabling the comparison of alternative products.

Temporal and spatial features

Apart from the type and focus of the model, time and space are relevant to modelling of physical flows. The aspect of time in models can either be static, comparative static or dynamic. In general, decisions do not result in a sudden transition of one state to another state. To analyze the transition paths between various states dynamic models are needed. To compare two states, comparative static analysis is sufficient. Moreover, the systems that are studied here are usually complex, large-scale systems subject to external conditions that continuously change in time. Nevertheless, in practice often static models are applied, where time aspects are not explicitly considered. The aim of comparative static models is the comparison of different values of a particular parameter (e.g., a situation with and without a specific policy) or the comparison of a parameter at two different points in time. Dynamic models are used for studying the behaviour of systems during a continuous or discrete finite time interval. In these models time is an explicit variable, which enables inclusion of changes in technology and demand, accumulation and time lags.

The spatial scale of a model depends on the problem that can be a local, regional, national, international or global issue. For environmental modelling the issue studied is an important factor in determining the spatial level of aggregation. Some examples of environmental problems at different spatial scales are given here.

- Global: global warming, deforestation, trade of toxic waste
- International: acidification, water pollution
- National: exhaustion or landfills
- Regional: pollution of ground water
- Local: soil pollution, noise, urban air pollution

Units, performance indicators and type of variables in economic models

The units in which economic models are formulated include prices, utility and quantities. Quantities are usually not specified in physical terms (e.g. kilograms or joules) or in environmental terms (e.g. depletion units or global warming potential) but in functional units (for example, goods or services). In economic models the physical quantities are not always considered explicitly, which may result in incorrect representation of real physical states or processes. In addition, performance indicators may be used. A performance indicator is a unit that is used to summarize or aggregate (a group of) physical, economic or environmental effects or results in order to allow for assessment and evaluation.

Additionally, the type of variables in the model are important for the interpretation and policy implications. Here, only endogenous and exogenous variables are discussed. Endogenous variables are determined within the model while exogenous variables are determined outside the model. For example, when modelling the total consumption of a certain good, the population may be included as an exogenous variable and the consumption per individual may be endogenously determined by the price of the good.

3. Materials flow analysis

A materials flow analysis or substance flow analysis (MFA or SFA) describes the flows of a specific material in a specific geographic area in a certain time period. An example is the flow of cadmium in the Netherlands in 1990 (van der Voet, 1996). Such a description allows one to analyze where the materials flow may be reduced or changed. It provides insight in the materials flow through the economy and also where materials are accumulated.

The method of MFA considers one or more materials flows. However, transactions between the different flows are not taken into account. MFA is based on the materials balance principle (see, for example, Ruth, 1993). The total flow of a specific material, thus including all products which contain or use that material, through the economic system is described and analyzed to trace missing flows of materials and to identify and predict environmental problems. MFA is a tool which supports the decision making on environmental policies. Static MFA studies describe the material flows without considering variation over time. Dynamic MFA studies analyze the (historical) materials flows over a certain time period. In these dynamic studies changes in extractions or use of materials may be incorporated. MFA studies are usually carried out on a national or regional level. However, MFA is also performed on a more detailed level, for instance, on a firm level. MFA studies seldom incorporate specific environmental indicators, but they provide information to derive some of these indicators.

The materials balance principle is used in MFA to analyze material and energy flows in the economic system, that is usually also confined to a specific region or country. Numerous examples exists of recent studies on the flows of one or more materials in a specific geographical area in a certain time period.[1] On the basis of MFA models may be built to analyze or estimate flows when certain policies are imposed (i.e. a scenario analysis). For the cadmium and nitrogen flow in the EU a descriptive model is used to estimate changes in

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[1] Heavy *metals* have been studied for several regions (see, Van der Voet *et al.*, 1994 and 19 96; Gilbert and Feenstra, 1994; Gorter, 1994; and Ayres, 1994). Various MFAs have been done for different types of *chemicals*, like nitrogen and sulphur (see, Ayres and Norberg-Bohm, 1992ab; Husar, 1994), and chromium and lead (see, Lohm *et al.*, 1994).

Examples of *regional materials balances* where the total flow of one or more materials through a specific region is studied are Brunner *et al* (1994) for a Swiss region, Ayres *et al.* (1994) for carbon monoxide and methane in the United States. The flows of heavy metals in river basins and in the Black Triangle is studied by Anderberg *et al.* (1989), Ayres *et al.* (1989), Ayres (1993), Bergbäck *et al.* (1992), Stigliani and Anderberg (1992, 1994).

Some *dynamic materials balance* studies have been done, e.g. for fly ash (Olsthoorn *et al.*, 1991).

materials flows if the scheduled policies are imposed (van der Voet, 1996).

Figure 1 gives an illustration of an MFA study in which the flows through the economic and environmental system are described. Interesting is that the accumulation in the economy and environment are visible. This accumulation may give rise to environmental problems now or in the future.

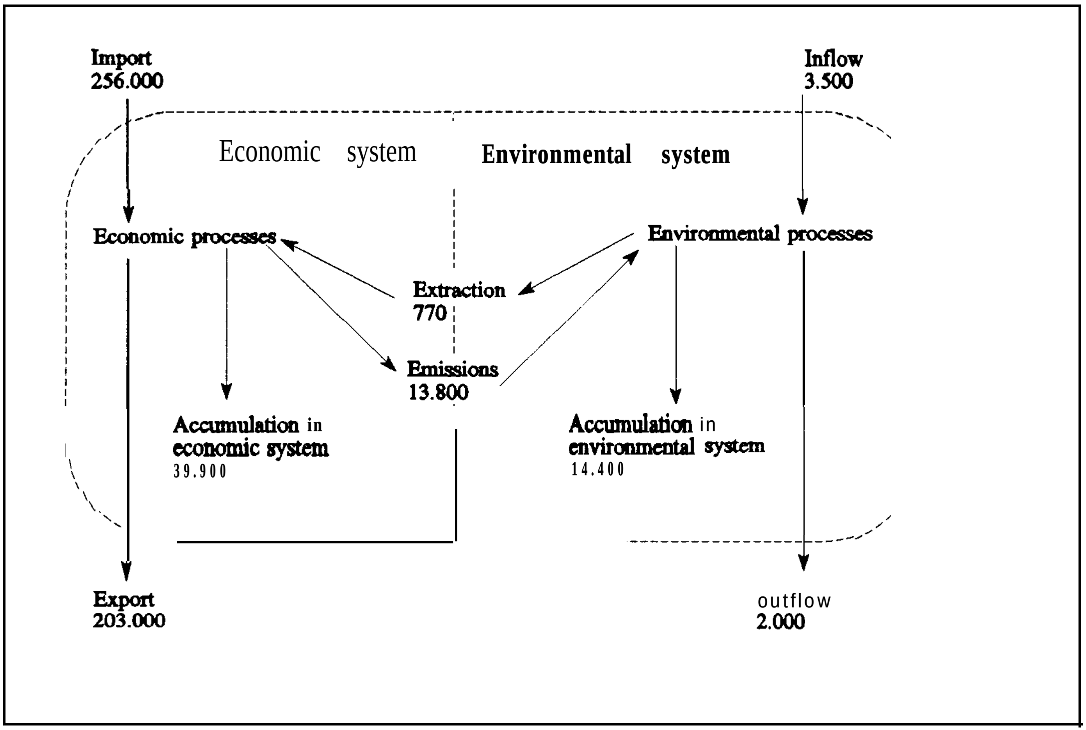

Figure I: MFA study on zinc flows in the Netherlands in 1990 (in tonnes) (adapted from Annema et al., 1995).

Because MFA studies usually result in a description of flows of materials, they are inappropriate to analyze societal, economic or behaviourial mechanisms. An example of this restriction is that substitution and complementarity between materials cannot be considered, because these are described separately and independently of the service they provide. Although these are behaviourial mechanisms and substitution are important issues for policy making, they cannot be easily analyzed using MFA.

MFA has it origins in I-O modelling in which the materials flows through an economic system are described. Physical I-O modelling will be discussed in Section 4. On the one hand, MFA may be seen as a part of a physical I-O table, namely the physical flows of the material that is studied. On the other hand, a physical I-O table may be seen as an aggregate of many materials flows, that even may be studied independently. The According to van der

Voet (1996; page 7) another origin of MFA are the detailed bookkeeping of agricultural materials. In practice, MFA is often more detailed for economic sectors that are important for the material studied.

4. Physical input-output analysis

Input-output (I-O) analysis was introduced by Leontief in 1941 and has been widely applied and further developed and modified (see also Leontief, 1966). I-O analysis is basically a quantitative macro-economic tool that is based on National Accounts. The basic purpose of the I-O framework is to analyze the interdependence of industries in the economy and therefore also the term 'interindustry analysis' is sometimes used (Miller and Blair, 1985). It describes, originally in monetary units, the mutual exchange of goods and services between the different sectors of industry and towards the final users. Analogous to monetary I-O models, physical models are elaborated based on the same philosophy. In bookkeeping the transactions between sectors, it is possible to account in physical or monetary terms. The accounting in monetary terms has the problem that changes in prices do not necessarily reflect changes in physical units. But accounting in physical units gives measurement problems because sectors normally sell more types of goods (e.g. a car may be a middle size or a small size car) (Miller and Blair, 1985). Physical I-O models use the materials balance principle, i.e. physical inputs equal outputs, while monetary I-O models do not use this principle.

This section presents a physical I-O table in which the physical interactions, i.e. inputs and outputs, of various sectors are described systematically. These may be used for analyzing environmental issues related to the use of materials or product flows. For environmental economic modelling I-O tables are often in monetary and physical units, for example, physical units for pollution and resource use and monetary units between sectors. Therefore, a basic monetary I-O table with resources and emissions is described here. Most I-O tables are in an homogeneous notation, with the industrial sectors and the corresponding groups of goods as the row and column elements respectively. This provides a square matrix if every sector has one output.[2] These enable calculation of, for example, the reaction of a national industrial system on the autonomous increase of the demand for a specific product

[2] The assumption that every sector produces one homogenous output is needed for making a physical I-O table. However, in reality there are various notes to make. Two important ones will be mentioned here. First, firms in one sector may produce different products and even one firm may produce different products. Second, when producing an output other products, co-products, by-products and waste are produced (see Heijungs, 1997). The multi-input/multi-output approach to materials and energy flows specifically deals with the various input and output flows of processes (Jansen and Lambert, 1996).

or product group.[3]

Input-output (I-O) analysis describes the transactions between the different economic sectors in the economy and the final users in monetary, physical or a combination of these units. I-O tables are mainly used to describe the sectoral structure of an economy. The interactions on a macro-level are described in monetary terms to obtain insight in the (level of) interdependencies between various sectors in one specific year. In an I-O table the interactions between two sectors are described. The ratios between inputs and outputs of two sectors are assumed to remain constant over time (fixed technological coefficients). This makes it impossible to incorporate substitution processes or technological change. This type of relationship, known as a 'Leontief production function', assumes constant returns to scale and full complementarity between inputs.

An I-O table (see Table 1) consists of the intermediate deliveries between economic sectors (AX, with A the matrix of input coeffkients in the economic sectors, and X is the vector of the output of the economic sectors), the deliveries from the economic sectors to the final demand (Y) and use of primary physical inputs to the economic sectors (LX, with L the matrix of input coefficients from primary inputs to the economic sectors). Vector E is the total of required primary inputs. The vectors X, E and Y are in physical terms. The first three rows of Table 1 present a standard I-O table which may be written as two equations: (i) $AX + Y = X$ or $X = (I-A)^{-1}Y$ and (ii) $E = LX$. The term $(I-A)^{-1}$ is called the Leontief inverse and represents the cumulative direct and indirect use of intermediate goods per unit of final good. The last two rows will be discussed later.

These three rows show the interdependencies between the economic sectors, the final demand, the resources and the emissions. It may be used to measure the effects of a change in the final or intermediate demand (X or Y) or the technical coeffkients (L and A) on all sectors. A strong point of I-O tables is that not only the direct effects can be calculated but also the indirect ones. The indirect ones may be calculated from the interactions between the sectors (i.e. the economic structure). For example, a decrease in the final demand of sector i affects the inputs of sector i. Then, if sector j supplies an input to sector i, the demand for the output of sector j is affected. Moreover, also the inputs required for sector j change, which may ultimately affect again sector i etc. Therefore, a change in the output of one sector may affect other sectors.

In analytical terms the primary inputs needed are a constant times the final demand, $E = LX = L(I-A)^{-1}Y$. When the total output (X) changes the primary inputs (E) change and when the final demand (Y) changes the pollution changes via the indirect or cumulated matrix of coefficients $(I-A)^{-1}$.

[3] An alternative is a commodity-by-industry (C-I) table (see Miller and Blair, 1985).

Table 1: An I-O table with resources and emissions.

	economic sectors	final demand	total output
economic sectors	AX	Y	X
primary inputs	LX	--	E
resources	cx	--	R
pollution	DX	--	P

The last two rows of Table 1 present the resource use of and the pollution generation, by the economic sectors. The resources (**R**) and pollution (emissions) (**P**) may be calculated via the direct impact coefficients (C for resources and D for pollution): $R=CX=C(I-A)^{-1}Y$ and $P=DX=D(I-A)^{-1}Y$.

The discussed tables are descriptions of the inputs and outputs of sectors. Based on these descriptive I-O models optimization models may be developed. In a standard I-O model the value added may be optimized under restrictions of the I-O model. With data on resources or pollution the emissions may be minimized under set of conditions, for example, a restriction on demand.

There are various differences between I-O models on the one hand and MFA and LCA (see Sections 3 and 5) on the other hand. First, I-O analysis provides for a complete description of industrial-economic systems, while MFA and LCA which are restricted to flows of specific materials and products, respectively. Second, I-O analysis defines statistically based relationships between sectors without going into detail regarding process properties. This restricts I-O modelling from a process point of view. In contrast, MFA and LCA include the inputs and outputs of specific processes. Third, the description by I-O matrices enables analysis of systems with complex mutual relationships.

5. Life-cycle assessment

Although several definitions of life-cycle assessment (LCA) have been proposed, the ISO-14000 definition has been set as a world-wide standard (ISO, 1995): Life-cycle assessment is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. It should be stressed here that LCA is intended for comparative use, so results of LCA studies have a comparative significance rather then providing absolute values on environmental impact related to a definite product. Therefore, in LCA two or more alternatives are compared. These alternatives may be existing products, but also potential new or improved products.

Essential to LCA is the 'cradle to grave' approach, referring to the study of the materials and energy flows related to production and consumption of a product from extraction up to final discharge. Effects of significant accompanying flows, such as energy, other utilities, capital goods, and by-products are all included, essentially leading to a branched process-product chain. Therefore, integration of social and economic aspects within the analysis is frequently advocated. Although various aspects of a product (economic, social, safety) during its entire life cycle may be studied, the concept of LCA is usually confined to a quantitative and environmental aspects based on physical flows. A LCA study directly relates to a product that is bought by consumers or final users.

Life-cycle assessment is carried out in five phases (see ISO, 1995; Guinée et al. 1993; Berg *et al.,* 1995). These phases are: (1) goal definition; (2) inventory of environmental inputs and outputs; (3) conversion of inputs and outputs to environmental impacts; (4) evaluation, i.e. comparison of environmental impacts to some standard (optionally); and, (5) improvement analysis.

Because of the branched character of the process-product chain, particularly if recycling is applied, a proper choice of system boundaries is crucial (Tillman et al., 1994). Within the model a core and a periphery can be distinguished: the core encompasses the part of the chain to be studied into more detail, e.g. because processes or products to be compared are crucial here; the periphery consists of auxiliary processes (e.g. electricity generation) and is rather coarsely described. Crucial data on the periphery are usually taken from a database, which is a compilation of results from restricted (product or process) LCA studies, not enclosing the full life cycle. The inventory part is directly related to physical flows.[4] Conversion, valuation and improvement analysis are interpretations of these flows.

LCA studies generally do not cover complete material balances, because for practical reasons only the environmentally most harmful flows are considered. However, a complete inventory of materials and energy use is recommendable because it may lead to valuable options for saving raw materials and energy. Although LCA is a potentially useful tool to perform a complete inventory, this is not accomplished. There are major data restrictions with respect to generality, actuality, level of aggregation and transparency of the way they have been acquired. LCA software supports the administration of required data, and a

[4] Partial analysis has been applied to non-discrete and discrete products. Discrete products is a product that is bought by a unit and a non-discrete product is bought by (kilo)grams. Among studies on non-discrete products are LCAs of building materials, energy carriers (Frischknecht, 1994), plastics, petrochemicals, paints and varnishes, margarine, hair sprays, detergents etc. (Guinee, 1995). Examples of discrete product studies are packaging materials, face plates, computer cases, automotive parts (Snowdon, 1994; Brinkley, 1994; Eyerer, 1993), automotive vehicles (Schuckert, 1993).

proper presentation of the results.[5] Uncertainties and data errors tend to exert a major influence on the final results, even in a comparative sense.

Environmental impact is characterized by multiple criteria, for instance energy use and acidification. In order to make these impacts comparable equivalence factors are used in the evaluation phase of the study. With weighted aggregation of the various environmental impacts, LCA results may be presented in terms of one or more environmental performance indicators (EPIs). EPIs are usually applied in financial and human resource management, and are strongly aggregated characteristics that reflect the performance of a complex system. EPIs can be aggregated into a single characteristic, for instance, the Material Intensity Per Service unit (MIPS) (see Schmidt-Bleek, 1993).[6] An example of an EPI in which a limited number of environmental impacts are considered is the Ecological Footprint (Wackernagel and Rees, 1996).[7] EPIs are applied to communication within environmental management systems and to external reporting. Like LCA, EPIs are only suitable for comparative purposes and do not provide any reliable absolute figure. Because most EPIs strongly depend on the applied weight factors, these should be well documented in reporting to guarantee adequate exchange of information and appropriate comparison of data. EPIs may be useful in communication directed to policy makers and stakeholders of companies, where recognizability and comparability are the principal requirements. For scientists these requirements are also valuable, but they aim at have less aggregated, more objective and more accurate data on the environmental impacts.

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[5] An example of a software tool for LCA of products is SIMAPRO (Guinée *et al.*, 1991). Specifically for window frames SIMAKOZA is developed (Guinée *et al.*, 1992).

[6] MIPS refers to one single figure, representing the total direct and indirect materials use related to a unit of service, expressed in mass units (kg), abstracting from the environmental characteristics of the different materials that are involved. This technique is primarily designed for providing clearly understandable information as applied (Fresenius Environmental Bulletin, 1993; Hinterberger *et al.*, 1995). Bringezu (1993) links LCA to MIPS to screen quickly the materials that are needed for a certain product or functional unit.

[7] The concept of 'Ecological Footprint' is an aggregate indicator. Selected flows of materials and energy needed to fulfil the human needs are calculated and converted into corresponding land area that is needed to support these flows. This land area indicator may be compared to the land area that is actually used by people in a geographical area (a region, a country). If the indicator is higher (more square meters) than the actual use, the ecological footprint is assumed not to be 'sustainable'.

6. Physical flow analysis and materials-product chain analysis

Although materials and products are strongly related on a physical base, the driving force for the consumption of products is the desire for services. Therefore, products and services should be studied together and simultaneously. The materials-product (M-P) chain analysis is an appropriate tool to study the interactions between demand, and the flows of products and materials. This method refers to a system or network which includes the full product life cycle: extraction, production and waste treatment as well as recycling, re-use and substitution of materials and products. M-P chain analysis is a combination of physical flow and economic modelling, which allows one to study physical, environmental and economic aspects of flows, but for practical reasons for a limited number of materials and product flows. M-P chain analysis may be seen as a combination of materials flow studies (MFA and physical I-O analysis), product life cycle analysis (LCA) and economic analysis.

M-P chains analysis may result in important insights about reduction of the environmental burden caused by the demand for a service. The essential aspects of M-P chain analysis, and the differences with the methods discussed in Sections 3 to 5 are listed below:

- Economic aspects, such as prices and costs of materials and products, and the behaviour of consumers and producers, are included because these influence the use of materials and products. Economic or monetary aspects are generally not included in LCA and MFA studies. In I-O studies these aspects are only incorporated on a highly aggregated level.
- Recycling of materials and re-use of products is fully included if it actually happens or may happen. In LCA recycling and re-use may be included too. In MFA at the other hand, recycling is taken into account only on the level of materials.
- M-P chain analysis incorporates substitution of different materials or products, and of materials and other inputs. MFA and I-O studies, in contrast, do not include substitution. To compare products LCA studies need to consider products that are substitutable.
- Both long-range changes in time, like technological developments, and short-range changes, like changes in demand, are considered. In other methods dynamic aspects are generally excluded. Recently, however, there are some MFA and LCA studies in which dynamic aspects are included (for MFA see Gilbert and Feenstra, 1994; and for LCA see Moll, 1993). Therefore, fundamentally there is no difference.
- The goal of M-P chain analysis is to analyze the effects of various instruments or policies on the physical flows and, environmental and economic indicators. The goal of LCA is to compare various products, and of MFA and physical I-O analysis to describe the physical flows.

Depending on the goal of the M-P chain analysis a certain part of the interlinked materials and product flows is chosen.[8] In principle, both descriptive and optimization models can be used (see Section 2). For an M-P chain analysis, one should be confined to a certain geographical area, that can be a region or a country. The environmental aspects (see, Section 2) can be dealt with separately or simultaneously. For example, to reduce the consumption of materials or the disposal of waste materials an M-P chain analysis can result in data on effects of a certain policy on this system. M-P chain analysis proceeds according to static, comparative static or dynamic models. The choice of the time horizon in dynamic models depends on the goal of the analysis. Services and products are the central issue of M-P chains. Thus, the aggregation level of this method is the micro level. For product groups meso level studies may be performed.

M-P chain analysis is, like LCA and MFA, limited by data availability and unpredictable future flows. Moreover, criteria are needed to truncate all the related materials and product flows, and assumptions need to be made on the uncertainty of prices and the reaction of policies on consumers and producers behaviour.

7. Evaluation and discussion of methods and characteristics

In this section the methods described in Section 3 to 6 will be assigned to the characteristics discussed in Section 2. It should be emphasized that this is meant as an indication of the differences between various methods. Table 2 presents some of these characteristics for the various methods. The strengths and weaknesses of the respective methods in relation to their different aspects of application are evaluated.

A physical flow is related to other physical flows, for instance the materials of which a product is made. Physical flows are embedded in an economic system that requires a certain number of products. Therefore, for modelling physical flows in an economic system two types of interfaces are important. First, interfaces between a number of physical flow models, to build models of more extended systems, e.g. product chains or interactions between different chains. Second, interfaces between the physical flow model, the economically and socially oriented systems and their relationships.

[8] Examples of M-P chain analyzes are dynamic simulation models that analyze the impact of several policies on the use of different products and materials to meet the demand for a service, for example, for the service of window frames which can be made of PVC, aluminum, hardwood or pine wood (see Kandelaars and van den Bergh, 1997). The effects of several economic policy instruments, such as, charges and deposit-refund systems, on the use of environmentally problematic materials can be studied (for example, PVC in Opschoor, 1994). For the service of rain-gutters a comparison has been made between zinc and PVC gutters, subjected to various policies, using static optimization and dynamic simulation models (see Kandelaars and van den Bergh, 1996; and Kandelaars et *al.,* 1996).

Type of model

The different methods of modelling have as a basis a description of the physical flows studied. The (historical) description may be extended to a model in which scenarios may be analyzed. Most MFA studies are descriptions. LCA studies, mainly descriptive as well, are usually applied to compare different products or processes. For I-O analysis and M-P chain analysis a description may be linked to an optimization model. And for M-P chain analysis to an equilibrium model.

Aggregation of the model

MFA and I-O models are mainly done on a sectoral level studying the flow of materials between sectors. The flows are generally studied for the whole economy. The aggregation level may be seen as a mixture between macro and meso. LCA and M-P chain analysis are on a more detailed level dealing with products and the whole production chain. This may be seen as a meso-micro level of aggregation.

Orientation of the models

MFA studies are physically oriented with a focus on environmental issues related to the materials described. LCA studies are physically orientated too, but the unit studied is a product or a service. Physical I-O analysis looks at the materials and products of sectors, which are mainly linked to economic sectors. M-P chain analysis studies the physical and economic aspects of a service or a product simultaneously. MFA, LCA and M-P chain analysis are also oriented towards environmental aspects. To physical I-O analysis depletion and pollution aspects measured in kilograms may be included.

Temporal and spatial features

Although MFA, LCA and M-P chain analysis may adequately deal with time series, in practice these analyses are not often done due to a lack of appropriate data. For all types of models, the impact of inaccurate input data should be evaluated by sensitivity analysis. All types of modelling are applicable to scenario analysis and other forecasting or evaluation techniques. I-O tables may be made for several years separately with different technical coefficients.

LCA and M-P chain analysis are usually confined to product or services. MFA and I-O analyses, however, refer to existing, sometimes extensive, geographic regions. Most MFA and I-O analysis are done on a national scale.

Units, performance indicators and types of variables

Of the four quantitative model types discussed in this chapter, MFA analyzes the physical flow of materials in kilograms (or tonnes) through the economy from and to various environmental components, such as air, ground and water. Thus, there is a link between environmental or economic units and the physical flow, but no attention is given to quantify these environmental or economic units. Physical I-O models analyze physical flows on a macro level which results in studying an aggregate physical flow measured in kilograms or Joules. LCA focuses on a product, which is in itself an economic unit, and measures the environmental impact in various environmental units (energy use, global warming potential, acidification) for the whole life cycle of the product. Although a product is the central focus, monetary units are not considered in the LCA studies so far. Monetary, physical and environmental aspects are considered in M-P chain analysis. Not all physical flows are taken into account like in MFA and I-O modelling, but only a limited number of flows which seem to be most important physically, environmentally or economically. Performance indicators may be used to aggregate various environmental variables to compare the environmental impact of, for example, different kinds of products.

Table 2: Overview of some characteristics of the modelling methods.

Method	Type	Aggregation level	Orientation	Unit studied
MFA	descriptive	national or regional level (macro)	physical	materials (kilograms)
physical I-O analysis	descriptive/ optimization	national or regional level (macro)	physical	materials (kilograms)
LCA	descriptive	product chain (meso)	physical and environmental	product (functional unit)
M-P chain analysis	descriptive/ optimization	product chain (meso)	physical, economic and environmental	service or product (functional unit)

8. Conclusion

From the survey of the most commonly applied physical flow modelling methods and M-P chain analysis, and the typology of their relevant characteristics, the following main conclusions are drawn:

- In present applications there is an emphasis on descriptive and static representation of physical flows. Recently, dynamic aspects are being considered, especially in M-P chain analysis.

- In many of the studies described in literature, the level of aggregation is relatively high. This is mainly due to difficulties of data acquisition, lack of knowledge of the exact flows of materials and products. LCA and M-P chain analysis study physical flows on a product or service level which allows one to examine the consumption side of product flows in detail.
- Physical flow models are useful in analyses that are characterized by a broad spectrum of temporal and spatial scales, level of aggregation and orientation. As has been pointed out, however, different modelling techniques may be suitable for different purposes.
- The need for accuracy and completeness of data is an issue that continually deserves attention.
- Substitution, recycling and re-use are important issues for the analysis of the environmental impact of materials and product use and therefore should be considered adequately. If recycling or re-use (may) happen it should be included in LCA and M-P chain analysis. Substitution is included on the level of products in LCA and M-P chain analysis. On the materials level only in M-P chain analysis. MFA and I-O analysis do not included substitution, recycling and re-use.

Physical flows result from the demand by producers and consumers for materials and products. This demand depends on economic factors such as prices and preferences. In MFA, I-O models and LCA these economic factors are not (fully) taken into account. The physical flows are described without looking at their economic basis. For researchers and policy makers it is important to obtain insight in the economic mechanisms underlying the physical and environmental ones. This implies the need for M-P chain analysis, which deals with physical, environmental and economic aspects simultaneously. From a physical and environmental perspective M-P chain analysis may be seen as a combination of materials flow studies (MFA, I-O analysis) and product life cycle analysis (LCA).

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